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FLUID PHYSICS, THERMODYNAMICS, AND HEAT TRANSFER EXPERIMENTS IN SPACE:

Final Report of the Overstudy Committee

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16. Abstract An overstudy committee composed of six academic and three industrial research scientists was formed to study and recommend fundamental experiments in fluid physics, thermodynamics, and heat transfer for experimentation in orbit, using the Space Shuttle System and a space laboratory. The Space environment, particularly the low-gravity condition, is an indispensable requirement for all the recommended experiments. The experiments fell broadly into five groups: Critical-Point Thermophysical Phenomena, Fluid Surface Dynamics and Capillarity, Convection at Reduced Gravity, Non-Heated Multiphase Mixtures, and Multiphase Heat Transfer. The Committee attempted to assess the effects of "g-jitter" and other perturbations of the gravitational field on the conduct of the experiments. A series of ground-based experiments are also recommended to define some of the phenomena and to develop reliable instrumentation.					
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SUMMARY

An overstudy committee composed of six academic and three industrial research engineers and scientists was formed to study and recommend fundamental experiments in fluid physics, thermodynamics, and heat transfer for experimentation in orbit using the Space Shuttle System and a space laboratory.

The low-gravity environment available in an orbiting space vehicle, combined when desirable with the vacuum and low-temperature heat-sink of space, makes it possible to explore new phenomena and to conduct tests over a much broader range of parameters than can be done on earth. The Space Shuttle offers the opportunity of conducting controlled experiments that take advantage of these characteristics of space.

The experiments recommended by the Committee fall into five major groups. Under the title "Critical-Point Thermophysical Phenomena", an initial exploratory series of experiments is recommended to find out what transpires when a fluid goes through a phase transition in low-gravity. Several specific experiments are then recommended on light scattering, on correlation length studies, on specific heat, etc. Under "Fluid Surface-Dynamics and Capillarity", experiments are recommended on static and dynamic contact angle hysteresis, on liquid configurations in containers, on the maximum amplitude of capillary waves, on standing waves in containers, on interfacial capillary waves, on droplet breakup and coalescence, on gas - and liquid-jet instabilities, on levitation, and on the spreading and production of thin films. Under "Convection at Reduced Gravity", experiments are recommended on surface-tension driven convection (effects of sidewalls, role of a free-surface, pressure and temperature variations in a heated, closed container, etc.) on thermoacoustic convection, on convection due to mechanical vibrations, electric fields, and magnetic fields, on solutal and thermosolutal convection, on convection driven by gradients in chemical potential, on coupling phenomena, and on thermally unstable flows. All of these types of convection are present on earth but are masked by the much larger gravity driven convection and thus can not be determined accurately. Furthermore, in space these may be dominant and very important. Under "Non-Heated Multiphase Mixtures", a series of experiments on aerosol mechanics, foam formation and stability, the dynamics of liquid-liquid dispersion, and the dynamics of bubbles are recommended. Under "Multiphase Heat Transfer" experiments are recommended on the effect of gravity on the boiling curve, on bubble forces, on bubble microlayer formation, on the Marangoni effect on bubbles, on the effect of electric, magnetic, and acoustic fields on boiling, on forced convection boiling, on condensation in tubes, and on solidification and cooling by liquid impingement. This report is not an exhaustive catalog of experiments, but rather a set selected by the Committee which in its view warrants special attention.

The Committee has tried to assess the effects of the space laboratory on the conduct of the experiments and the degree to which non-controlled variations in gravity will affect them. Non-uniformities in the steady gravity field can be as large as $10^{-5} g_0$. The Committee feels that this difficulty can be largely overcome by conducting experiments during the drift mode of the Space Shuttle. Time variations in the gravity field (g-jitter) caused by astronaut motions, mechanical vibrations, and vehicle control measures are potentially more serious. The Committee recommends that further research be conducted to define the g-jitter environment and to relate it to the proposed experiments.

The Committee feels rather strongly that the Principal Investigator for each experiment should take an active role in its conduct and that, ideally, he or one of his co-workers should direct the experiment in space; in any event, he should be able to receive information and give instructions while the experiment is in progress.

Finally, a series of ground-based studies are recommended to define the phenomena to be observed in some of the experiments and to develop reliable instrumentation.

INTRODUCTION

The NASA Space Shuttle will offer scientists and engineers the opportunity to conduct controlled experiments in fluid physics, thermodynamics, and heat transfer phenomena. The space environment can be greatly beneficial for these experiments because the nearly weightless conditions in orbit, combined with a hard vacuum and a large low-temperature heat-sink, will allow parameter ranges and phenomena to be explored that would otherwise be difficult or impossible to achieve. NASA Lewis Research Center has sponsored the present independent overstudy by a committee of university and research-institute engineers and scientists to identify fundamental experiments in fluid physics, thermodynamics, and heat transfer which are scientifically meritorious, timely, and particularly well-suited for a space environment.

As the contractor for the overstudy, Southwest Research Institute was charged with forming a committee composed of a representative number of prominent scientists and engineers. A broad coverage of all the pertinent fields of study was to be obtained by selecting individuals each of whom had background in the experimental and theoretical phases of some pertinent area of the overstudy. Previous experience in space-related research, although thought to be perhaps desirable, was not considered a requirement for selection. It is clear that there are large numbers of qualified scientists who could have made valuable contributions to the study but, naturally, only a few could be asked to serve. Since the committee members were also asked to solicit suggestions from their colleagues, the degree of participation of the scientific community is certainly wider than merely the committee itself. In addition, several previous studies (refs. 1 through 6, and others) that identified some promising areas and specific experiments were to be critically reviewed, as were the results of the relatively uncontrolled experiments conducted on some of the past Mercury, Apollo, and Skylab flights.

Six academic and three industrial research scientists ultimately comprised the Committee. H. Norman Abramson, Vice President of the SwRI Division of Engineering Sciences, has extensive experience in free surface dynamics and fluid interface phenomena. Stanley W. Angrist, Professor of Mechanical Engineering, Carnegie-Mellon University, an expert in applied thermodynamics, surveyed the fields of fluid physics and heat transfer as applied to the technology of manufacturing processes. Ivan Catton, Associate Professor of Thermal Sciences, University of California at Los Angeles, a specialist in heat transfer processes, convection, and free surface fluid mechanics, examined experiments in the areas of thermally-driven turbulence, convection caused by non-gravitational field forces, and some capillary flows. Stuart W. Churchill, Carl V. S. Patterson Professor of Chemical Engineering at the University of Pennsylvania, a member of both the National Academy of

Engineering and the Universities Space Research Association on Convection and Heat Flow, and an expert in heat transfer and rate processes, examined the experiments considered in multiphase phenomena. Franklin T. Dodge, Senior Research Engineer in the SwRI Department of Mechanical Sciences, has worked extensively in fluid surface waves in low gravity and capillarity, and investigated experiments in these areas as well as experiments related to stability of flows with interfaces. Richard J. Mannheimer, Staff Scientist in the SwRI U. S. Army Engines, Fuels, and Lubricants Laboratory, who is an expert in surface chemistry, rheology, and capillarity, investigated experiments related to foams. Simon Ostrach, William J. Austin Distinguished Professor of Engineering at Case Western Reserve University and a member of the Universities Space Research Association on Convection and Heat Flow, surveyed convection experiments as well as some experiments on capillarity and contact angle phenomena. Sidney H. Schwarz, Associate Professor of Mechanical Engineering and Engineering Mechanics, West Virginia University, is an expert in boiling and multiphase heat transfer, areas in which he investigated a number of experiments. Jan V. Sengers, Professor at the Institute for Molecular Physics, University of Maryland, directed the committee's efforts in critical point thermophysical phenomena.

F. T. Dodge served as the committee chairman and was responsible for coordinating all of the committee's activities and for providing the administrative services of Southwest Research Institute as required to support these activities.

The procedures followed by the Committee were, in the main, the usual kind for a body that could meet as a whole only a few times during its existence. There were three meetings of the entire committee, comprising a total of five days. Most of the detailed work was done in the periods between the meetings. Each member was asked to prepare a list of promising experiments, not necessarily restricting himself to his particular area of expertise, and to document them in a form suitable for consideration by the other members. These experiments were critically reviewed by the Committee as a whole, and improved if necessary or even deleted in a few cases. Judgments were made concerning the relative merits of single experiments or groups of similar experiments. These activities took up most of the first two meetings. The third meeting encompassed a final review of all the experiments described in this report, and decisions of the group as a whole were made concerning the final list of recommended experiments. The impact of the environment of the space laboratory on the experiments was also discussed, and recommendations for preparatory ground-based research were made. It should be emphasized that the intent of the Committee was not to compile an exhaustive list of experiments, but to make specific recommendations of meritorious experiments.

The style of presentation of the experiments deserves some explanation. In most cases, the experiments are described only conceptually because the primary emphasis is placed on the scientific objective of the experiment and the benefits to be expected from conducting it in space. Mathematical formulations have been held to a minimum, and the figures are designed to aid the understanding of non-experts rather than to present hard data. This style, although perhaps not completely satisfying to a reader interested in the details of a given experiment, is meant to make the report appeal to a broad spectrum of scientists. It is hoped that the references cited for the experiments can supply the needed back-up scientific information.

The Committee wishes formally to acknowledge the valuable participation of the NASA technical monitor, William J. Masica, who assisted with the conduct of the study.

DISCUSSION OF EXPERIMENTS

There are both practical and basic research reasons for conducting experiments in space on heat transfer, fluid physics, and thermodynamics. Since the laboratory is in a state of near free-fall around the earth, space experimentation has the advantage of a weightless, i. e., low-gravity, environment. This combined with a practically unlimited hard vacuum and a low-temperature heat-sink, means that many analyses and experimental correlations involving gravity as a parameter can be evaluated over a wider range than is practical on earth. It also provides a way to eliminate the perturbing effects of gravity and therefore makes it possible to study phenomena that might be suppressed on earth. A few examples will illustrate these benefits of space experimentation and introduce some of the important concepts.

On earth, studies of interfacial and capillary phenomena often must be limited to ultra-small geometric scales in order either to emphasize capillarity effects in comparison to gravity, or to diminish the possibility of gravity-induced Rayleigh-Taylor instabilities at an interface. A reduced-gravity environment allows the experiments to be conducted on a much larger scale, thereby making accurate observations possible.

Gravity effects can mask other phenomena, thereby hindering their study on earth. For example, dynamic, drag, and surface tension forces on bubbles in nucleate boiling are difficult to evaluate on earth because of the large buoyancy force; in space, however, this force can be diminished to a negligible level. On earth, flows induced by buoyancy (natural convection) can cause unwanted secondary effects in many experiments. Buoyancy-induced flows are minimized in low-gravity, which is one of the reasons why much enthusiasm has been expressed for space manufacturing of metals and crystals in space. Many types of convective flows are possible, however, and some of these may become prominent when natural convection is no longer present to mask them. The principles which govern the conditions for which a non-gravity-induced convective flow is likely to occur are not known with certainty. Space experimentation can provide the basic understanding needed to define the nature and significance of these flows.

In many cases, the only feasible alternatives to testing in space are by the use of drop towers----allowing the experimental apparatus to fall freely for several seconds----or sounding rockets. Some valuable results have been obtained in this way, but the available duration of weightlessness with a drop tower is too short to study many important phenomena and, with sounding rockets, all experiments must be automated or controlled remotely.

Space experimentation is, however, not without its own problems. These are discussed later in detail, but one important consideration should be mentioned now. Many of the proposed experiments require that the effective gravitational field be maintained at a known orientation and at a constant, uniform level of $10^{-4}g_0$ to $10^{-6}g_0$.^{*} Unfortunately, the Skylab experiments have shown that time-dependent, high-frequency perturbations on the order of $10^{-3}g_0$ can be present even during a drift mode or coasting orbit. The Space Shuttle is a much more rigid structure than Skylab, and so might not be so susceptible to this "g-jitter". However, perturbations even of the magnitude of the uniform gravitational field would certainly affect or possibly spoil many of the proposed experiments.

Each of the experiments in fluid physics, thermodynamics, and heat transfer that was identified by the Committee and considered to be meritorious is discussed below. The only significance to the order of presentation is to discuss the experiments by groups in a logical sequence of no flow, flow but no heat transfer, flow and heat transfer, multiphase flow, and multiphase heat transfer. Many of the experiments are interrelated and share a commonality of experimental equipment.

Critical Point Thermophysical Phenomena

The subject of thermophysical properties and phenomena near the critical point of fluids, as well as phase transition phenomena in fluid systems in general, appears to the Committee as the most interesting topic in thermodynamics for experimentation in a space environment. We refer here to the gas-liquid phase transition in fluids and to the phenomena of phase transition in liquid mixtures.

The importance of low-gravity experiments in the area of critical phenomena and phase transition phenomena in fluids arises from the conjunction of a number of factors.

1. The extent to which theories of critical phenomena in fluids can be tested experimentally on earth is limited because of the variation of the density of fluids with height caused by gravity.

* g_0 is the value of gravitational acceleration at the earth's surface.

2. The universality of critical phenomena implies that low-gravity experiments with fluids will contribute to an understanding of the behavior of many kinds of physical systems other than the fluids actually studied.
3. When a fluid undergoes a transition from one phase to two, gravitationally driven sedimentation is the dominant mechanism for the spatial separation of the two phases.
4. The information obtained from such experiments will relate to recent theoretical and experimental work involving a significant portion of the scientific community.

When fluid systems proceed through a phase transition on earth, gravity causes the phases to separate into two distinct regions. In a gravity-free environment, the dominating forces will be interfacial and capillary, and the dynamics of the phase transition process will be very different. Furthermore, near the critical point, fluids exhibit an anomalously large response to gravity. As a result, experiments near the gas-liquid critical point on earth are severely affected by inhomogeneities of the fluid sample resulting from the height of the sample.

The past decade has brought a renaissance of the study of critical phenomena. A large number of scientists are currently actively involved in the subject and further advances are assured. It seems most probable that the activities and progress will extend into the subject of first order phase transitions as well. Thus the space experiments will be conducted at a time of unprecedented interest and expertise in phase transitions. Experiments in a space laboratory on the subject of phase transitions and critical phenomena are likely to enhance this progress further.

Exploratory Experiments

As a first step the Committee recommends that exploratory experiments be conducted simply to find out occurs when a fluid goes through a phase transition at low-gravity. In particular two experiments are recommended, one concerning the gas-liquid phase transition and one concerning the phase separation in a binary liquid mixture.

In their most elementary form these experiments can be described as follows.

Take a set of samples of a one-component fluid with different densities. Included should be a sample at subcritical density, a sample at the critical density and a sample at supercritical density. Let the temperature vary either continuously or discontinuously through the transition temperature and take photographs at regular temperature intervals. Compare these photographs with those obtained at earth under the same instrumental conditions. Conduct similar experiments for a set of samples of a binary mixture at concentrations smaller than, equal to and larger than the critical concentration.

An experiment definition study should be made to decide which systems should be selected and at which densities and concentrations.

On earth a meniscus will appear at the bottom, somewhere in the center, or at the top of the cell, depending on the density or concentration. In space the true equilibrium state at densities sufficiently away from the critical density is probably that of one large spherical liquid droplet located somewhere in the vapor, if we ignore the effect of the walls. However, it seems plausible that in practice a multiplicity of domains of the liquid phase may be formed. It would be of interest to observe the size distribution of these domains both as a function of the rate of change of the temperature and at a given temperature as a function of time. Near the critical point, the thermodynamic fluctuations become very large and the domain size distribution could become stationary. The domain structure is likely to be affected by the presence of the walls. Therefore, it may also be of interest to conduct these experiments with samples of different geometry, but with the same density or concentration.

The experiments are likely to enhance progress in nucleation theory. When the phase transition takes place on earth, the influence of gravity upon the process is overwhelming. As the temperature of a fluid or a fluid mixture is changed to bring it into a thermodynamic state in which phase separation is thermodynamically favored (whether near or far from the critical point) inhomogeneous nucleation will usually occur. Since the phases are almost invariably of different densities, the earth's gravitational field will cause relative motion of the two phases. In a very short time the effects of the nucleation are felt throughout a macroscopic sample because the growth of the separate phases is aided by gravitational sedimentation of the phases into layers of differing density. The importance of gravity in this process is dramatically illustrated in attempting to reverse the process by restoring the temperature of the fluid to its former value. It may take 100 times as long for the fluid to become homogeneous as it did for it to separate into distinct phases. In a high-g environment, surface and diffusive phenomena are dominant only in the early stages and on small size scales of phase separation.

In a low-g environment, the rate of sedimentation will be greatly reduced and the important roles of surface and diffusive phenomena will become much more visible. One may expect domains of the separating phases to grow slowly. The effects of inhomogeneous nucleation will not be propagated as rapidly, thus permitting homogeneous nucleation to be more readily observed. The phenomenon of spinodal decomposition, recently observed in a binary liquid mixture (ref. 7) may become more readily accessible and could perhaps be also observed in a pure fluid. For these and other purposes it may be advisable to include some other optical observations such as light scattering. In the case of a binary mixture one may also look into the possibility of using a mixture whose two phases have a different color.

The equipment needed for these experiments could also be used for some of the fluid mechanics experiments described else where in this report.

Exploratory experiments of the type described in this section are strongly recommended for the following reasons: the experiments can be readily conducted using existing technology and instrumentation; the same instrumentation can be used for a variety of other experiments; the experiments would seem to guarantee some results which may even be spectacular; the experiments are conducted at a time of considerable scientific activity and progress in the subject; the theoretical expertise for interpreting these experiments is available; and the results will serve as a guide for more sophisticated subsequent experiments.

Specific Experiments Near the Gas-Liquid Critical Point

In the vicinity of the critical point many thermodynamic and transport properties of a fluid exhibit anomalous behavior. Some of these anomalies, such as those in the compressibility and the thermal conductivity, are strong and are noticed over a large range of temperatures and densities around the critical point. Other anomalies, such as those in the specific heat C_v and the shear viscosity, are weak and can only be observed close to the critical point. The critical behavior is associated with the presence of density fluctuations that extend over a correlation length ξ which diverges as $(\Delta T^*)^{2/3} = \{(T - T_c)/T_c\}^{-2/3}$, where T_c is the critical temperature. At a temperature $\Delta T^* \approx 10^{-6}$ this correlation length is somewhere between 1000 Å and 10,000 Å.

Since the compressibility is strongly divergent, gravity produces a large density gradient in a fluid near the critical point. On earth, any given fluid sample at equilibrium near the critical point is stratified according to

density as illustrated in figure 1. Near the critical temperature the density can readily vary by as much as 5% over a height of only 1 mm (ref. 8). Hence, only a vanishingly small portion of a macroscopic sample can be very near the critical density itself. Furthermore, because of the inhomogeneity in density produced by gravity, the correlation length on earth can not in practice exceed approximately 10^{-4} cm in the vertical direction.

The Space Shuttle provides the unique possibility of conducting measurements near the critical point on fluid samples that are essentially homogeneous. Such experiments are therefore guaranteed to produce valuable information independently of the direction in which our theoretical understanding may advance. The potential benefits of experiments on critical phenomena in space are twofold: (1) a number of anomalies which are only barely observable on earth can be studied accurately; and (2) the static and dynamic behavior of fluid systems in which the correlation length is no longer small compared to the size of the experimental probe can be studied accurately. The fundamental variable governing the behavior of a system near the critical point is the correlation length. Since this correlation length is large compared to the range of the intermolecular forces, the behavior becomes independent of the details of the interaction and has a universal character. Therefore, accurate experiments in space on one suitably chosen system should yield insight concerning the behavior of all other fluids near the critical point.

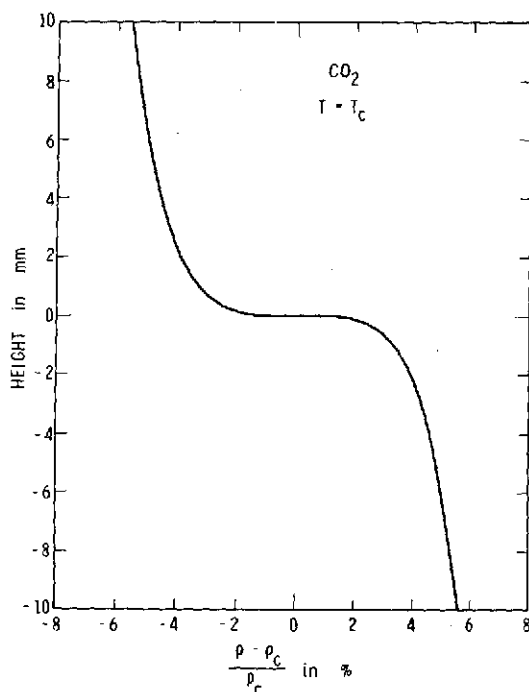


Figure 1. Density as a function of height in the earth's gravitational field for a sample of carbon dioxide in thermodynamic equilibrium at the critical temperature

Below a number of specific experiments are listed whose relevance is already apparent. The Committee does not claim that this list is complete. Moreover, in view of the rapid development of the subject, it is to be anticipated that additional experiments will recommend themselves in the near future. In each experiment it is recommended that the data be taken as a function of temperature for a sample at the critical density. Information as a function of density is also desirable, but is less urgent and could be considered subsequently.

Specific heat. - The heat capacity C_V diverges as $C_V \propto |\Delta T^*|^{-\alpha}$, where α is probably greater than zero, but smaller than 0.15. The subtle divergence of the specific heat at constant volume is fundamentally connected with the nonanalytic character of the equation of state at the critical point. An accurate determination of the anomaly in C_V has turned out to be very difficult as a result of the density gradient introduced by gravity. When the sample temperature is changed, matter has to be redistributed to establish a new density profile; this process gives rise to latent-heat contributions (ref. 9 and 10). Thus the experimental specific-heat versus temperature relation is severely distorted at all temperatures where density gradients are present. An experiment in near-zero gravity would avoid these complications and could yield definitive information on the behavior of the specific heat and the value of the exponent α . An adiabatic calorimeter with stepwise or continuous heating techniques would seem most suitable for the purpose. The technology for conducting calorimetric measurements at $\Delta T^* \approx 10^{-6}$ is available and similar experiments have been done in helium near the λ -line (ref. 11 and 12). However, they have not been applied with the same precision near the gas-liquid critical point since the gravity-induced gradients did not justify the effort.

Light scattering. - A wealth of information can be obtained by measuring the statistical distribution of photons scattered through the fluid at various angles. Such measurements yield the density-density correlation function as a function of wavelength and time. Suitable quantum electronic detection techniques have been developed in recent years. The intensity of the scattered light as a function of the scattering angle yields the correlation length, which is the variable needed to interpret all other experiments. By varying the position of the laser beam one can check whether the sample is indeed homogeneous.

At temperatures somewhat away from the critical temperature, the time variation of the density fluctuations can be described by the macroscopic hydrodynamic equations. Here, the spectrum of the scattered light yields the thermal diffusivity. When the critical temperature is approached more closely, a nonlocal description of the dynamics is required. The decay of the fluctuations is also expected to deviate from simple exponential behavior. Two attempts have been proposed to describe these phenomena

which yield similar results away from the critical point but different predictions in the immediate vicinity of the critical point (ref. 13). These theories are likely to be refined in the near future, but in earth-bound experiments near the gas-liquid critical point, it is difficult to discriminate between them because of experimental errors caused by gravity (ref. 14). In the subsequent stage it may be possible to approach ΔT^* values of 10^{-9} ; then one could possibly probe the static and dynamic behavior of samples whose correlation length is of the order of the size of the laser beam itself. Under similar instrumental conditions on earth the density would vary appreciably over the size of the laser beam.

Dielectric constant and refractive index. - There exists both theoretical and experimental evidence that the refractive index exhibits an anomalous behavior near the critical point (refs. 15 and 16). Experiments indicate that the anomaly is of the order of 5×10^{-4} at $\Delta T^* \approx 10^{-6}$ (ref. 17), but theory and experiment are not in good agreement. The experimentally observed anomaly is again severely affected by gravity effects, and it is extremely difficult to investigate the phenomenon in any quantitative detail on earth. In space the refractive index could be measured by determining the phase shift of the transmitted light relative to the incident light beam. Therefore, such experiments could possibly be combined with the light-scattering experiments mentioned earlier.

The anomaly is also likely to show up in the dielectric constant. Anomalous behavior of the dielectric constant can be investigated using a stack of capacitors (ref. 18). This experiment is interesting because it cannot be done on earth (because of the density gradient between the plates) and one has a built-in check to verify that the sample is homogenous by comparing the dielectric constant as measured by the different capacitors. This experiment is also of fundamental interest, since measuring the local dielectric constant or refractive index is often used as an experimental method to determine the local density in a fluid near the critical point.

The dielectric constant should be determined with a precision of at least $1:10^5$. However, as in most other involving critical phenomena, relative precision is sufficient and absolute accuracy is not required.

Velocity of sound. - The possibility of measurements of the sound velocity should also be considered. Suitable techniques for measuring the sound velocity near the critical point are available (ref. 19 and 20). Again the experiments on earth are subject to gravity corrections (ref. 9). In the zero-frequency limit the sound velocity should vanish as $C_v^{-1/2}$. Therefore, low-frequency sound velocity measurements provide an alternative method of determining the exponent α .

Measurements of the velocity dispersion and the attenuation of sound provide information concerning the critical dynamic behavior at wavelengths and frequencies different from those probed by light-scattering techniques.

Diameter of the coexistence curve. - The law of the rectilinear diameter states that the sum $\rho_L + \rho_V$ of the densities of the coexisting liquid and vapor phases varies linearly with ΔT^* . However, modern thermodynamic characterization of the critical point inescapably implies that the law of the rectilinear diameter cannot be strictly correct and that the diameter $\rho_L + \rho_V$ should vary asymptotically as $|\Delta T^*|^{1-\alpha}$. Most attempts at measuring this anomalous behavior of the diameter have been unsuccessful. The anomaly is small and will only show up in a region where gravity effects are important (ref. 21). Thus the anomalous behavior of the diameter could be another phenomenon which might be characterized by experiments in a space laboratory.

The procedure for measuring the coexisting densities will probably be very much influenced by the results of the previously recommended exploratory experiments.

Viscosity. - There exists strong evidence that the shear viscosity also shows an anomalous behavior near the critical point (ref. 22), although the anomaly is a weak one and cannot be measured very accurately on earth. The capillary-flow method is unsuitable for measuring viscosity near the critical point, and the recommended method is measuring the damping of an oscillating or rotating cylinder. On earth the precision is limited by the density variation in the sample along the cylinder, but these limitations disappear at low gravity. These measurements could resolve some theoretical controversies whether the viscosity remains finite or is truly divergent.

Thermal conductivity. - The thermal conductivity is strongly divergent and appears to increase approximately in proportion to the correlation length ξ (ref. 22). However, since both the thermal expansion coefficient and the specific heat at constant pressure diverge even more strongly, namely approximately as ξ^2 , all conventional thermal conductivity measurements on earth are affected by free convection when the critical point is approached (ref. 23).

Among the available techniques for measuring the thermal conductivity, the transient hot wire technique is the most suitable for use in space. This method is faster than the stationary method, it can be readily digitalized, and the experiment possibly could be combined with the fluid mechanics experiments concerned with convection around a heated wire. The precision of the transient hot wire technique has recently been improved considerably (ref. 24). The method has the disadvantage that it does not

measure the thermal conductivity directly but the thermal diffusivity instead. The information to be obtained is therefore somewhat similar to that obtained from line-width measurements of the Rayleigh line in the spectrum of scattered light. Nevertheless, these separate thermal diffusivity measurements are of interest, because the method is capable of yielding thermal diffusivity values with a higher precision and over a larger range of temperature. Furthermore, it yields the thermal diffusivity at a macroscopic wavelength of the order of the size of the probe. Thus the method will yield information different from that provided by light scattering, when the correlation length is not small compared to the wavelength of light.

Experiments Near the Critical Mixing Point of a Binary Liquid

As was mentioned earlier, it is equally interesting to study the dynamics of phase separation in binary liquid mixtures at low-gravity. In the earth's gravitational field, the effects of nucleation are felt throughout a macroscopic sample in a very short time, since the growth of the separate phases is aided by sedimentation of the phases into layers of different density. In low-gravity, the rate of sedimentation will be greatly reduced and the roles of surface and diffusive phenomena will become dominant. Experiments in the metastable states may also become more readily accessible. Binary and multicomponent systems also offer the possibility of studying a much larger variety of phase separation and critical phenomena than those occurring in one-component fluids (ref. 25). For instance, it would be intriguing to study liquid-liquid-vapor equilibrium under gravity-free conditions.

Near the critical mixing point the issues are in principle similar to those concerning the behavior of fluids near the gas-liquid critical point. That is, the behavior of the system is again associated with a diverging correlation length. In a gravitational field the true equilibrium state is accompanied by concentration and density gradients (refs. 26 and 27). The existence of gravity effects near the critical mixing point has been demonstrated experimentally in a high gravitational field (ref. 28). There exists, however, some uncertainty as to the time scales in which thermodynamic equilibrium is reached. The formation of concentration gradients is the result of diffusion and sedimentation, and the rate of diffusion becomes vanishingly small near the critical point, while the rate of sedimentation increases because of the divergence of the corresponding Onsager phenomenological coefficient.

Experiments studying phenomena near the critical mixing point of liquid mixtures in space are likely to be uniquely valuable. Even if gradients are not formed within the time rate of most earth-bound experiments, the fact remains that these experiments refer, in principle, to

nonequilibrium states. On the other hand, in space we may be able to prepare states which are at equilibrium and at the same time homogeneous. More exploratory research would be needed to establish the feasibility of preparing a homogeneous sample near the critical mixing point. In view of the long equilibration times, it must be done by first preparing a homogeneous sample slightly away from the critical point and then approaching the critical point by changing the temperature in a uniform manner. The question of relaxation to equilibrium in binary mixtures is currently under active investigation and more insight may be expected in the near future.

If exploratory studies indicate that homogeneous equilibrium samples can be prepared at low gravity, then most of the experiments mentioned for the gas-liquid critical point are also recommended for fluid mixtures near the critical mixing point. In addition, some other experiments should be considered, such as measuring the thermal expansion coefficient, which is expected to diverge with the exponent α . The subject is of sufficient interest that further preparatory studies are desirable.

General Experimental Requirements

Critical phenomena experiments of the type described require a temperature regulation and stability with a precision between $1:10^6$ and $1:10^7$. Temperature stability of this precision is now commonly realized on earth in experiments near the critical point. Additional new phenomena will be observed if the temperature can be regulated at $1:10^8$ or $1:10^9$. Critical phenomena experiments with a temperature resolution at the $1:10^8$ level are currently being successfully conducted on earth by a few investigators.

The duration of the experiments will be determined by the time needed to reach equilibrium. The equilibration time is proportional to the correlation length, and, hence, increases when the critical point is approached. The equilibration time is determined by diffusion and thermal diffusivity (ref. 8) as well as the distances to the thermal walls and the geometry of the apparatus. From experience with earth-bound experiments, we may estimate that the equilibration time for experiments near the gas-liquid critical point will be of the order of several hours. For experiments near the critical mixing point of liquid mixtures the equilibration time poses a problem which needs to be studied in more detail as discussed earlier.

Because of these special requirements the critical phenomena experiments are recommended as second generation experiments. However, it might be desirable that some of the exploratory experiments suggested earlier be conducted so as to obtain valuable information for designing these second generation experiments.

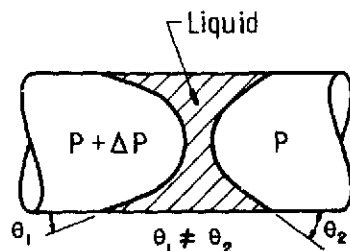
Fluid-Surface Dynamics and Capillarity

Many interesting phenomena occur at the interface between two fluids. Earth-based studies of interface phenomena are often limited to small geometric scales to increase the influence of interfacial forces and to minimize Rayleigh-Taylor instabilities. Larger geometric scales can be obtained by using two immiscible liquids that have almost identical densities, but, if the objective is to study the dynamics of a liquid-gas interface, this simulation method distorts inertial effects severely. Drop-tower testing gives an accurate low-gravity simulation, but test-durations are very short and all observations must be made remotely or photographically. The Space Shuttle provides an opportunity to observe interface phenomena accurately and, thus, to resolve many of the controversies and inadequacies of our understanding by permitting larger-scale experiments without instabilities caused by gravity. Alternatively, the instabilities themselves can be studied on a much slower time scale. For these reasons, many Mercury, Apollo, and Skylab flights have included experiments on interface dynamics.

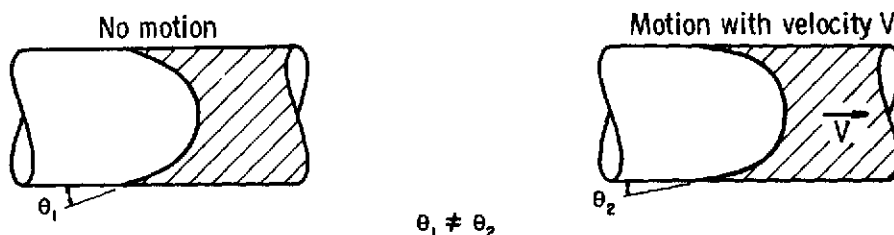
Dynamics of Fluid Interfaces

On earth fluid interfaces tend to be dominated by gravitational field forces, whereas in a low-gravity environment surface tension and contact angle effects can be dominant. Therefore, whole classes of interface and capillarity phenomena become accessible to observation in space. The experiments described in this section are considered by the Committee to be among the more important of the many that would benefit by being conducted in space.

Static and Dynamic Contact Angle Hysteresis. - There are many fluid surface problems for which a fluid-fluid interface--commonly a liquid and a gas, or a liquid and its vapor--meets either a solid surface or the surface of a third fluid. The line of intersection is called the "three-phase line," or as the "contact line" for the special case of a liquid-solid-gas intersection, and the angles formed by the intersection are called the "contact angles," θ . Unfortunately, the contact angle is not always a uniquely defined property of the three components. For example, when a liquid droplet is placed on an inclined solid surface it is observed that as the inclination is increased the droplet deforms and the contact angle changes; eventually the droplet begins to move after the inclination exceeds some critical value. The first published study, apparently, of the resistance of a droplet to movement is ref. 29. Several studies have been reported subsequently. The study reported in ref. 29 involved a liquid droplet in an air-filled capillary tube across which a pressure differential was applied, as shown in figure 2a. It was observed that (1) the droplet could withstand an appreciable pressure differential before



(a) Static contact angle hysteresis



(b) Dynamic contact angle hysteresis

Figure 2. Types of contact angle hysteresis

moving and (2) the static contact angle exhibited hysteresis. Possible causes of the observed hysteresis include roughness and heterogeneity of the solid surface, the presence of contaminants, the absorption of a molecular film on the solid surface, and the penetration of the solid surface by liquid molecules. To date, no definitive explanation of this phenomenon exists.

As a further example of contact angle phenomena, when a three-phase line moves slowly over a solid surface it appears as though the interface is sliding, but such an observation is at odds with the fact that a viscous liquid cannot slide over a solid surface. Differences of opinion have arisen, consequently, as to whether a droplet slides or rolls over a solid surface. Adding more confusion to the characterization of the contact angle is the observation that the contact angle generally depends on the velocity of the three-phase line, as is illustrated in figure 2b; this is called dynamic contact angle hysteresis. Although the contact angle is a fundamental variable in the thermodynamic treatment of all capillary systems, an adequate hydrodynamic explanation of dynamic contact angle hysteresis is lacking. The work of ref. 30 is the most advanced but still indicates the need for more detailed observations of the phenomena.

Since the contact angle plays such an important role in many fluids problems, its nature and character must be understood. The physical processes occurring at the three-phase line have not yet been unequivocally described. Experiments conducted previously were limited to capillary tubes to reduce gravitational effects, and thus, since the geometric scale was small, observations in the region of interest near the wall were almost impossible and therefore not definitive. The reduced gravity of space provides the opportunity to resolve many of the existing problems by careful, large scale experiments with a much diminished influence of Rayleigh-Taylor instabilities.

To study the static contact angle, drops of different liquids should be examined on various types of solid surfaces to determine the influence of surface roughness, porosity, cleanliness, etc., on the contact angle. To study the nature of static and dynamic contact angle hysteresis, a slug of liquid of varying physical characteristics in an air- or vapor-filled tube should be subjected to an axial pressure gradient, first to observe the resistance of the liquid to motion and then to cause flow. The tube should be large enough to permit detailed and accurate observation to be made of both the advancing and receding contact angles. Particular attention should be given to the fluid film deposited and adsorbed on the surface during motion. This is a crucial aspect of the current theories. Subsequent tests should be made with curved surfaces as well as flat ones.

Liquid Configurations Under Reduced Gravity. - Storage of liquids is another example of a problem which is gravity-dominated on earth and capillary-dominated in low-gravity. It is, further, of great practical interest in the design of spacecraft tankage. In a gravity-dominated environment the position of the liquid in the storage vessel is well defined, but the influence of surface tension, contact angle, and body forces can lead to some unexpected configurations in the capillary-dominated regime. For certain kinds of vessel geometries, typically two plane vertical walls intersecting at an angle α such that $2\theta + 2\alpha < \pi$, where θ is the contact angle, the theory predicts that an equilibrium free-surface is not possible; that is, the surface deforms continually (refs. 31 and 32). Free-surface shapes in non-axisymmetric tanks, such as a toroid tilted with respect to the g-vector, can be very convoluted in reduced gravity and almost impossible to predict theoretically. Earth-based tests generally are either on a scale too small to enable accurate observations to be made or of a duration that is too short to eliminate transients when drop-towers are used. Therefore the actual low-gravity environment of space would be very useful in studying equilibrium free-surface shapes.

Further, even when the most stable equilibrium position is known, the position or configuration of the liquid is uncertain during times when the net acceleration vector is changing in magnitude or direction. The transient time required to obtain a new equilibrium position after such a change in the effective gravity level can at present be only roughly approximated. These transient times are long because the surface tension driving force is small. Several oscillations or a disintegration of the surface can occur before all transients damp out.

A series of experiments is proposed to investigate the influence of the various physical and geometrical parameters on the equilibrium configuration, the nature of intermediate configurations after the fluid is disturbed, and the transient time to reach an equilibrium configuration. These experiments could be done on a modest geometric scale and would require a series of small containers of different shapes and made from different materials (to vary the wettability). Various fluids with different viscosities, surface tensions, densities and the like would then partially fill the containers. The experiments could be performed either during a constant-g coasting phase of a flight to determine equilibrium shapes, or during an acceleration phase of orbital flight to study transients and flow. Possibly a variable-speed centrifuge could be used to obtain various rates of change of g , if Coriolis forces can be shown to be negligible.

Surface Interface Waves in Low Gravity. - The theory of surface and interface waves has been a fruitful area of study for hydrodynamicists, and a reduced-gravity environment offers the possibility of quantitatively observing these waves when they are dominated by capillarity. Several practical reasons exist, also, for studying low-gravity surface-waves, such as spacecraft control and design of fluid transfer systems for space application.

The surface waves of interest are (1) standing and traveling waves on an unbounded surface and (2) standing waves in a container, where the boundary conditions largely determine the wave characteristics.

Linear or small-amplitude capillary waves on an unbounded surface are well understood. The advantage of a low-gravity environment lies in studying large-amplitude capillary waves, because the much reduced gravity force allows the wave length, i. e., the wave size, to be made large, thus making quantitative observations possible. In particular, the traveling and standing low-gravity waves with the maximum possible amplitude are of particular interest in hydrodynamics. When gravity forces are paramount, the maximum possible amplitude occurs just as the downward acceleration of the wave crest equals one g_0 : in other words, the liquid cannot withstand tension. For these conditions, Stokes showed in 1880 that a traveling wave with the maximum possible amplitude had a pointed crest enclosing an angle

of 120° , and Penney and Price showed in 1952 that the maximum amplitude periodic standing wave had a pointed crest enclosing an angle of 90° . When gravity forces are much reduced or absent, the liquid at the crest of the capillary wave will be in tension when the downward acceleration requires a force greater than that available from surface tension, so this determines the maximum amplitude wave. No theory for these waves, either traveling or standing, exists at present. The renewed interest in capillary waves evident during recent years will, however, ultimately result in theories being developed, and experimental data to guide the theory or to confirm it will be necessary.

These experiments on standing waves on unbounded liquid surfaces might be conducted by using a rectangular tank with a large length-to-width ratio (i. e., an essentially two-dimensional tank). The two vertical walls at the ends of the tank should be capable of mirror-image rocking motions to create a symmetrical wave, similar to the apparatus described in ref. 33. The liquid should have a 90° contact angle on the container wall to eliminate static curvature effects, and the contact angle should not exhibit any hysteresis. Perhaps the method of coating the walls to obtain a 90° contact angle that is described in ref. 34 can be used. A similar tank with one movable wall and a wave absorber at the other end might be used to study traveling waves. It would obviously be beneficial to conduct preliminary studies to help define the feasibility of this experiment.

Standing waves in a container, as contrasted to waves on an unbounded surface, are strongly dependent upon the boundaries when the wave length is of the order of the container size; these "fundamental" wave modes are of much concern in spacecraft stability studies. In low-gravity, surface tension and the effects of the boundary caused by static contact angle, contact angle hysteresis, and the tank shape determine the characteristics of the fundamental wave modes. The present analytical formulation (ref. 35) of the compatibility requirement relating the wave amplitude at the wall to the free-surface curvature, the container-wall curvature, and the contact angle is as yet open to question. Further analytical difficulties arise because of contact angle hysteresis. For example, the work reported in ref. 36 showed a 15 percent upward shift in natural frequency when water was used as a test liquid in a tank 2.65 cm in. diameter as compared to methanol or carbon tetrachloride for similar values of the other governing parameters. The water appeared not to "slide" freely along the tank walls. This implies that experiments should employ a wide range of fluids and tank materials in order to vary the wettability, to evaluate the influence of contact angle hysteresis, and in particular to study the motion of the surface at the contact line. The experimental apparatus could be a modification of that used in the transient liquid-configuration tests.

Interfacial waves between two superposed liquids and the associated forms of Rayleigh-Taylor instability should also be studied in low-gravity. When body forces are large, interfacial tension helps to stabilize the interface between two liquids. In a low-gravity environment, however, surface tension may promote instability because the minimum total-energy configuration of each liquid can be a sphere, if this is a possible configuration considering other restraints on the liquid. It is likely that a liquid layer in low-gravity is stable for small-amplitude interfacial waves whereas for some combinations of surface tension and liquid-layer thickness, large disturbances might cause the liquid to break up into one or more spherical droplets, whenever this is the true minimum-energy configuration. Other forms of instability will be present as well. Experiments to study these effects could consist of several closed tanks partially or completely filled with two immiscible liquids. One liquid should occupy substantially less volume than the other in order to emphasize the droplet break-up instability, and the dimensions of the containers should be at least an order of magnitude greater than this liquid layer thickness to minimize edge effects.

Capillarity

A number of experiments on fluid mechanics which are controlled by capillary forces are recommended by the Committee.

Droplet Formation, Breakup, and Coalescence. - The formation of droplets, and their breakup or coalescence when exposed to various kinds of external fields, is important in many varied applications. Uniform spherical capsules are formed by the disintegration of a liquid jet (ref. 37). Atomization of gasoline by acoustic fields is used to improve combustion and decrease emissions of gasoline engines. Wet scrubbers for removal of contaminants from gases use atomization to increase the surface area of the scrubbing liquid. The breakup and coalescence of droplets control important phenomena in cloud physics. All of these applications have in common a need to understand and control the dynamics of droplets. Low-gravity will allow much better control of experiments designed to obtain knowledge about the fundamental mechanics of these droplet phenomena.

The nature of the interaction between droplets depends on the sizes of the drops, their velocities, angular momenta, surface electronic charge, and the kinds of external fields to which they are exposed. Electrically-neutral droplets breaking up in an electric, acoustic, or thermal field can produce multiple, charged drops. Acquiring data on droplet breakup and coalescence is difficult on earth because gravity makes detailed observations about these processes almost impossible. In low gravity, studies of the relative importance of such variables as surface tension and viscosity would be greatly

simplified. A wider range of forces and conditions could be applied without the constraints of a wind tunnel or of mechanical supports; droplet energies could be controlled more readily; and the prolonged test times available when there is no gravity-induced velocity will permit detailed observations of the droplet surface before, during, and after applying an external field, or the collision mechanics of a multi-droplet experiment. Correlations of numbers and characteristics of generated droplets with field strength and frequency would become possible.

A 0.1 m³ chamber with controllable temperature, pressure, and gas composition would be adequate for these experiments on the effect of external fields on atomization. A drop, or group of drops, would be projected into the chamber, and the acoustic or electric field applied. Droplet velocities, distributions, and positions after atomization would be the primary observables. Strobe photography and holographic techniques would provide ideal visualization of the surface motions. Surface active agents and several different liquids should be used.

Another intriguing droplet experiment would be to measure--for the first time--the statistical-fluctuation dipole moment of a spherical droplet (ref. 38). It should be possible, in principle, to observe two small droplets accelerate slowly toward each other, thereby deducing the distance-force relationship, which according to theory should vary as the inverse sixth power of the relative separation. The obvious advantage of a low-gravity experiment is that the extremely small relative accelerations can be observed just by waiting long enough. Droplet charges might be thought to interfere with this experiment; however, they would produce accelerations with a different dependence on relative separation. Furthermore, the charges could always be measured by applying an electric field and their effects subtracted.

A droplet production experiment would be useful to earth-bound metallurgists. Utilizing the space environment, a Rayleigh particle-generator (a vibrated liquid-jet nozzle) could be used to produce non-oxidized spherical metal particles of uniform size. The experimental set-up would consist of an apparatus which would allow various size droplets to be produced at will by using a heavy-duty loudspeaker as a signal generator to control the disintegration. Various nozzles and an arrangement for collection of the drops produced would also be needed.

Stability of Liquid and Gas Jets. - Gas jets in a liquid and liquid jets in another liquid or gas, which find use in many liquid systems, are known to be unstable and to disintegrate readily. Jet dynamics continues to be studied as a form of hydrodynamic instability, and several applications, such as droplet or capsule formation, are apparent. The instability mechanism for liquid jets originally proposed by Rayleigh is purely temporal; that is, the

amplitude of the surface wave grows only with time at a given downstream location. Recently it has been shown that a temporal instability can not be applicable to a jet and that the true mechanism is that the growth of the amplitude of the perturbation depends only on the distance downstream of the jet exit nozzle (ref. 39). According to this theory, the mode corresponding to the Rayleigh instability is not the most rapidly growing. On the other hand, experiments (ref. 37) seem to indicate that the droplet sizes formed by the breakup are in fact related to the wavelength of the Rayleigh mode. Uniform spherical droplets can be formed by vibrating the jet nozzle at a frequency that gives a disturbance with a wavelength of about 4.5 times the jet diameter (the Rayleigh-mode wavelength) and this is the most stable operating condition (ref. 40). Satisfactory operation is obtained with longer wavelengths (up to ten diameters) but shorter wavelengths result in randomly sized droplets and erratic behavior.

Several experiments on liquid- and gas-jet instabilities are proposed. The mechanics of the instabilities are difficult to establish by ground-based experiments because of the effect of gravity in perturbing the trajectory and the circular cross-section of the jet and in limiting the scale and the types of experiments that can be used.

The length of a liquid jet before it disintegrates into droplets is determined primarily by stability criteria, whereas the length of a gas jet is determined both by stability and by the momentum of the jet that is available for penetration of the surrounding liquid. In normal gravity, it has been found that for gas jets gravity effects generally cause an instability in which the surrounding liquid pinches off the jet into discrete bubbles. In low-gravity, however, the instability of the jet and the initial momentum both play a role in determining if bubbles are pinched off or if a single cavity of fixed size is formed (ref. 34). As mentioned previously, the basic criteria for instability of a liquid-jet are still uncertain, so low-gravity experiments with their enhanced capillarity and increased geometric scale will be definite asset. It is almost mandatory to study gas-jet instabilities in low-gravity.

The proposed liquid-jet experiment would use circular nozzles of different diameters to eject various liquids into vacuum. These tests, which have some commonality with the droplet production and droplet coalescence studies, should be run through a wide range of velocities to determine the basic mechanisms of instability. The gas-jet experiments will be somewhat more difficult to conduct. The liquid into which the gas is injected should not have a free surface, in order that surface waves will not influence the jet instability; on the other hand, the liquid obviously must be free to expand, so that a free surface seems necessary. This conflict can be resolved by injecting the gas considerably below the free surface. Various values of liquid-gas interfacial tension should be used, and the momentum, diameter,

velocity, and density of the gas stream should be varied as well. Ground based studies to acquire fundamental understanding of jet instabilities would be beneficial.

Thin films. - As mentioned earlier, many interesting events take place at the surfaces of substances. Surfaces are invariably interfaces; that is, at every surface two material systems, are always in contact and interacting. Matter in its three states forms five interfaces: solid-solid, solid-liquid, solid-gas, liquid-liquid and liquid-gas. At almost all interfaces the interaction between the systems is mediated by thin films. For this reason thin films fully warrant the careful attention that has made investigation of them an important discipline of physics and chemistry.

The low-g environment of a space laboratory will maximize the effect of surface tension forces while the vacuum will facilitate control over undesirable oxides. These conditions might result in greatly improved smoothness on thin film surfaces produced in space, which would surely be of importance to various technologies. Furthermore, in order to carry out tests of the strong coupling theory of super-conductivity one needs to produce clean, evaporative, thin films of reactive metals, and space should be able to provide the conditions needed to produce such films. A thin film production process might also be useful in fabricating thin sections of steel for use in making transmission electron micrographs, which have proved to be extremely useful in metallurgical research. At present, rolling methods can fabricate sheets of steel having a thickness of about 0.003 inches. In general, the development of simple thin film production techniques, in particular metallic films, would have great significance in the field of electronics.

One method of thin film production which should be investigated is bubble casting. In this technique a molten material is blown into a mold to form hollow, thin-walled containers, a process which is made feasible because of the surface tension of the molten material. The space environment should enhance the surface tension effect and reduce contaminants to a minimum. The proposed experiment on bubble casting will require a crucible and a heat source of several kilowatts. One or more nozzles will also be needed to form the bubble from the molten metal. A method of delivering the metal to the nozzle under slight pressure will be required to produce the bubble at the nozzle tip. The bubbles should be blown in a closed container that can be vented to space. The container should be equipped with a viewing port.

Another experiment related to thin films is the phenomenon of a liquid film spreading on the surface of another liquid or solid. This spreading can be observed more readily in low-gravity for two reasons: the velocity during that phase of the spreading which is dominated by body forces is much reduced thus allowing more time for study, and the films that can be used are much thicker and therefore easier to instrument. The motivation for these studies encompasses such varied applications as the spreading of a weld pool on a metal surface, the spreading of an oil slick on calm water, and the diffusive spreading of liquid atoms in a metal surface (refs. 41 and 42).

The spreading of liquids could be studied by releasing known quantities of liquid on the surface of a solid or of another liquid. The test containers might be mounted in a slowly rotating centrifuge to produce a controllable low-g acceleration perpendicular to the surface. Instrumentation to measure the velocity profiles in the liquid would be valuable in clarifying the existing discrepancies in liquid spread theories (ref. 43). The film thickness, pool diameter, and leading-edge velocity as a function of time should also be measured.

Effects of Levitation

Various schemes have been proposed to levitate liquid masses away from container walls in a reduced-gravity environment. These include light pressure, strong acoustic fields, and electromagnetic body forces produced by inductors supplied from a source of high-frequency current. Levitation in low-g would be a potentially useful process for producing ultra-pure materials in the hard vacuum of space because it would provide experimenters with a wall-less crucible. The Committee has given some thought to these applications and other experiments that might benefit from low-g levitation.

During containerless solidification of pure materials one might expect cavities to be formed in the interior because of solidification shrinkage and lack of feeding. Surface solidification and the subsequent cooling leads to a contraction which is compensated for by plastic deformation. As deformation ends, a cavity forms at the liquid-solid interface. Perhaps this process could be studied initially on earth by stressing the interface during solidification. Cavity-forming activity would certainly inhibit the formation of perfect metallic spheres--a task frequently thought to be easy to carry out in space.

A number of experiments can be proposed that would take advantage of the wall-less crucible and hard-vacuum environment of space. One of the simplest is the study of the solidification of a freely floating sphere consisting of a single-phase alloy. This kind of experiment would take advantage of

the purification due to the hard vacuum and the absence of a container, and the low convection currents within the melt during solidification. The combined effect of these factors on structure, microsegregation and macrosegregation could be determined. Some suggestions have been made that these experiments be extended to include materials which become amorphous upon freezing. A similar experiment could be conducted on dispersions of solids in liquids and of liquids in liquids, using liquids which have substantial differences in density. One variant of this experiment would be to use a magnetic field to produce directional solidification of non-contained eutectic materials. Another experiment would be the containerless solidification of a two-phase alloy with strong under-cooling. It has been suggested that containerless cooling of under-cooled materials which are known to become amorphous would be unlikely to extend glass-forming regions unless this cooling is accelerated by other means, such as splat cooling. The study of the cooling of amorphous materials such as glass is potentially of great industrial importance. Container contamination is a factor that is known to be responsible for self-damage in laser glass.

Convection At Reduced Gravity

It is a common mis-impression that natural convection cannot occur in low-gravity (say $10^{-6}g_0$) and, therefore, that no fluid motions can be expected. This has resulted in much enthusiasm being expressed for manufacturing processes in a reduced gravitational environment. In some situations, however, it may be desirable to have fluid motions in space processing, e.g., to stir the fluid phase vigorously for purposes of mixing or cooling. The extent and nature of fluid flow in space cannot, at present, be predicted because natural convection and other spontaneous fluid flows may still arise under some conditions. The misconceptions about fluid flow at reduced gravity prevail because non-gravity forces that could generate flows in such an environment are generally overshadowed in a normal gravitational field and are, therefore, unfamiliar. Furthermore, the principles governing the conditions under which any sort of natural convection is likely to occur are also unfamiliar or as yet undefined, or are confused because they are complex. In actuality there are a variety of non-gravity forces, as well as gravity, that can induce fluid flow. Such non-gravity driving forces include surface or interfacial tensions, thermal-volume expansions, density changes caused by phase change, and magnetic and electric fields. Gravity-induced convection, furthermore, can still be appreciable even at $10^{-6}g_0$ under certain conditions. Some evidence of fluid flows in space flight are reported in refs. 44 and 46.

A description of possible low-gravity mechanisms for fluid convection will follow. Since a more basic understanding of these phenomena and extensive quantitative data are needed to define the nature and significance of such flows, a number of experiments to these ends will be suggested.

Surface-Tension Convection

Convective fluid flows can occur that are driven by gradients in surface tension. Several specific experiments are described below.

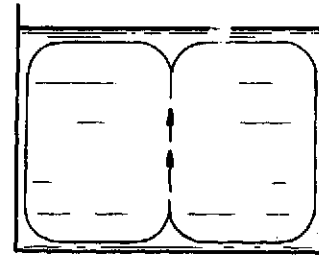
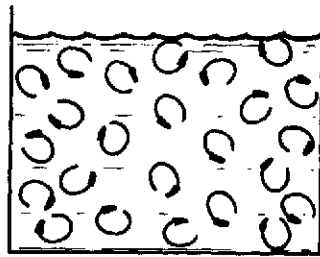
Effect of Sidewalls on Marangoni Flow. - Surface-tension driven cellular convection was obtained in experiments performed on the flights of Apollo 14 and 17 (refs.44, 45 and 46). There are some basic differences between the related theoretical papers (refs.47 and 48) and the experimental results. Reference 46 indicates, in particular, that the critical Marangoni numbers (for the onset of motion) were higher than theoretically predicted. This discrepancy was tentatively attributed to a possible difference in the temperature gradient in the liquid layer. However, in a similar situation with gravity-driven cellular convection, the effects of the confining boundaries were found to be highly stabilizing, i. e., the onset of motion was delayed. With the exception of ref. 49, no theoretical or experimental work has appeared in the literature concerning edge effects (adhesion, aspect-ratio, and thermal conditions) on cellular motion induced by surface tension. Not only are edge effects important with regard to stability but they may also play an important role in determining the shape of the cell pattern (and, hence the rate of heat transfer) which results after the motion starts (ref.50). It is therefore clear that edge effects are crucial to all aspects of surface-tension flows of this type.

A series of experiments are proposed to investigate the problem comprehensively, viz., to find the effect of container aspect-ratio, sidewall "wettability", and thermal conditions on the onset of Marangoni (surface-tension) flow and on subsequent cellular patterns. This fundamental and important information can be obtained from a rather simple experimental procedure for which there is already some space-flight experience. The basic equipment would be pan-like containers with diameters up to approximately 10 cm. The bottom surface would be a heater capable of supplying up to 8 watts. The end-wall materials and thermal and wettability conditions would be varied. Fluid layers of the order of 2 to 5 mm would be established in the containers and the heater turned on. The sequence of resulting events can be recorded by a motion picture camera. The duration of each test would not exceed 10 to 15 minutes.

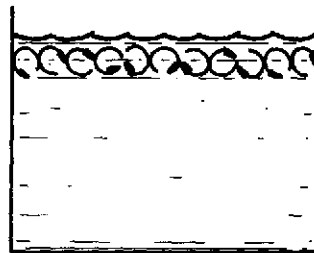
The paucity of information on this problem indicates the necessity of both theoretical and experimental work prior to space flights.

Role of a Free Surface on Reduced-Gravity Heat Transfer. - Heat transfer between the environment and a fluid in a open container can be expected to change significantly as the gravity level is reduced. For example, in a $1-g_0$ field the natural convection may be turbulent (fig. 3a), while in

reduced-gravity the gravity force might still predominate over other forces such as surface tension but the natural convection could be quite different i. e., it could be laminar, cellular, or both (fig 3b). In these situations the free surface can be said to be passive in the heat transfer process in the sense that the fluid motion is induced by buoyancy. However, as the gravity force is further reduced the surface tension becomes dominant and there will be negligible gravity-induced convection. In this case, the free surface may play an active role in the heat transfer process because of the flow generated by surface-tension gradients (fig. 3c). Therefore, it is important to determine the nature of this flow as a function of the geometrical configuration, boundary conditions, container materials, etc. The penetration of this flow into the fluid away from the free surface should also be determined because it will influence the heat transfer. Although in many respects convection resulting from surface and interfacial tensions is similar to that generated by gravity there are two important differences. One is the direction of flow and the other is that surface tension can cause convection in fluid layers cooled from below whereas gravity cannot. These aspects should be examined in detail.



(a) Gravity driven in $1-g_0$ (Turbulent) (b) Gravity driven in $10^{-6}g_0$ (Laminar)



(c) Surface tension driven in $10^{-12}g_0$

Figure 3. Modes of convection as a function of g -level

The apparatus for this experiment could be similar to that for the study of the side-wall effects on Marangoni convection, although the containers should be able to hold larger fluid volumes. Somewhat more instrumentation will also be required to define the flow and temperature fields in greater detail. Thus, thermocouples or liquid crystal tapes (as were used in the experiments on Apollo 14 and 17) will have to be utilized.

Pressure and Temperature Variations in a Heated Closed Container. -

The development of a set of reliable equations for correlating temperature and pressure in a heated, closed container of liquid and vapor will be useful in the design of fluid storage tanks both on earth and in space. Applications in space include the storage of fuel and of fluids for life support systems and heat transfer equipment; earth applications include the transport and storage of LPG and LNG and, in the future, perhaps of liquid hydrogen.

Several thermal convective regimes exist within a heated fluid. Under some conditions the gravity-induced buoyancy force will dominate, but when the gravity field is small enough, other driving forces, such as those related to surface tension and thermoacoustic phenomena, may dominate. Experiments in low-gravity should be conducted to define the limits of each regime and to understand better the thermal convection mechanisms. Experiments in the buoyancy-dominated regime will also be of value in extending data acquired at normal gravity so that correlations can be obtained. It is desirable to cover a wide range of values of the Grashof number (the ratio of buoyant to viscous forces) by using different fluids, but there are several problems associated with this approach for earth-based experiments. Reference 51 shows that many other dimensionless groups associated with this problem also include liquid and vapor properties, and hence it would be difficult, if not impossible, to keep each group at the same value while testing with different liquids on earth. However, experiments over a wide range of gravity levels with a single fluid can produce a wide range of Grashof numbers while holding the other groups constant.

The temperature distribution may change enough when the gravity level is low to make other transport mechanisms important. No mathematical models except pure conduction have been found which predict the temperature distribution under these conditions even though, when the liquid-vapor interface becomes curved, surface tension effects may begin to affect the stratification profile, particularly in the vicinity of the interface. Measurement of these changes and the critical values of the dimensionless groups when the changes begin to take place should add to the total understanding of the process of internal convection.

The principal objective of the proposed experiment will be to determine the pressure history and the transient temperature distribution within a heated container of liquid and vapor, with the liquid either in a quiescent mode, driven only by thermally produced driving forces, or by operating a mechanical mixing device to mix the fluid. The results would be correlated with the important dimensionless groups and compared with existing correlations and mathematical models. Pressure and temperature will be measured as a function of time for various heating conditions, gravity level, liquid height, and energy required by the mixing device.

The cylindrical tank design in a recently completed study of stratification at 1-g₀ and at high gravity levels produced by a centrifuge (ref. 51) might serve as a design guide for the low-g study. The tank could be heated by placing individually controlled blanket-heaters over its external surface and encapsulated in a polyurethane-foam insulation or placed in a large container which would be evacuated for thermal protection. A vent valve, located at the top of the container, and mixing system are needed. Limited 1-g₀ data (ref. 52) suggests that a jet-mixing system using an axially-directed nozzle located at the bottom of the tank and connected to the outlet of a centrifugal pump is adequate. Instrumentation requirements include thermocouples, a pressure transducer, a flow meter to monitor the mixer jet-velocity, and variable power-supplied for the heater blankets. A data acquisition system for immediate data referral and for permanent data storage is also required. The test-time and power needed depend on the fluid or fluids selected, the tank size and geometry, and the number of available gravity levels. The total time required for all tests, including time between tests to settle the liquid, is on the order of 50 to 150 hours, with the longest single experiment requiring approximately 3 hours. The energy needed will be of the order of 10 to 50 KW hours with a peak of less than 1 KW. Manual operation of the experiments can be minimal. The main value of an observer will be to detect unexpected results or malfunctions.

Ground based experiments are necessary both to check out the total experiment system and to provide data at the upper range of Grashof numbers which will be correlated with the low-gravity data. These experiments must be conducted prior to the orbital study and should be reverified after return to the earth, if practical.

Thermoacoustic Convection

In the absence of gravity, thermal-volume expansions can act as the driving force for convection. Rapid heating of a confined fluid causes rapid local expansions which, in turn, generate pressure waves. The pressure waves produce a convective motion that can greatly increase heat transfer relative to conduction and can also cause the transport of mass and chemical species, thus providing a mechanism for enhancing or suppressing convective motion at low-gravity by controlling the heating rate.

Although the effects of sonic and ultrasonic vibrations on gravity convection have been studied in some detail, only a few papers present experimental evidence on purely thermally generated acoustic waves. Reference 53 discusses the phenomenon of sound production when a glass bulb with a long open neck is heated (Soundhauss phenomenon). The Soundhauss phenomenon is not dependent on gravity but depends only on the expansion of air within the glass tube. Sound pressures of about 150 dB and velocities of about 10m/sec are reported for heat inputs of about 500 watts. The production of sound waves in a water-salt solution by means of an electrically heated transducer is reported in ref. 54. Acoustic signals produced by means of laser-generated thermal stresses are described in ref. 55.

It does not appear that any experimental studies have been performed with the aim of determining the extent to which thermoacoustic convection causes the heat transfer to deviate from pure conduction. Relevant to the possibility of sustained steady convection caused only by thermal volume expansion is the suggestion in ref. 56 that temperature oscillations can be caused primarily by compressibility effects. Also relevant is the phenomenon of acoustic streaming, which is the pattern of steady vortices in a fluid subjected to a steady acoustic field. This type of motion is caused by a non-linear coupling of the fluid-particle velocities. Thus far, acoustic streaming caused only by thermal-volume expansions does not seem to have received any attention. Recently, thermoacoustic convection has been studied numerically by means of a simple one-dimensional model (ref. 57). It was found that (1) the thermally-induced wave motion is acoustical, (2) thermoacoustic convection can greatly enhance the heat transfer rate, and (3) the magnitude of thermoacoustic convection depends strongly on the thermal boundary conditions.

The experiments required to gain insight into this phenomena can be of relatively small scale. The apparatus would consist of closed rectangular and circular containers into which would be placed gases such as carbon dioxide and helium. Heaters would have to be contained in the walls (in the cylindrical ones, e. g., at one end). The sidewall would be insulated and the other end cooled to maintain ambient temperature, and they would have to

be able to produce rapid heating at a variety of controlled and measured rates. The first phase of this test program would be to define how rapid the heating must be to generate thermoacoustic convection. This must be done for a variety of geometrical configurations and aspect ratios because the pressure wave reflections are important. Then, quantitative relations between heating rate and resulting convection must be determined as functions of the geometry, and, if possible, details of the velocity and temperature fields should be obtained. Each experiment would require only a few minutes because steady state is attained on that sort of time scale. The pressure can be measured with a transducer, and the heat flux density and temperature at both ends measured with heat flux gauges and thermocouples, respectively. Ground-based experiments should be run to guide the space experiments.

Convection Resulting From Mechanical Vibrations

Low frequency (from less than one hz up to 1000 hz) and low amplitude vibration of spacecraft produce effects equivalent to gravitational accelerations of up to $10^{-3}g_0$. This effect is commonly referred to as "g-jitter". Sources for such bumps or impulses in the spacecraft include motion of the occupants, attitude control measures, and internal mechanical events. In ref. 58 the effect of the fluctuations on a contained fluid were considered to be transferred to the fluid by normal and shear stresses. The former are associated with velocity fluctuations whereas the latter are attributed to orientation changes caused by relative motion between boundary surfaces and the enclosed fluid. Under the assumption that the shear stresses account for most of the convection, a relation was obtained between the Nusselt number (a comparison of random convection to pure conduction heat transfer) and the elapsed time between impulses for various geometries. The analysis considers only small amplitude vibrations and does not take into account substantial fluid flow that would result from large amplitude disturbances. An increase in heat transfer of between 300 and 400 percent is predicted during frequent impulses of small amplitude. Application of the analysis to the best vibration data from Apollo 14 (ref. 46) indicated a similar increase in heat transfer should have occurred but the actual measurements found the heat transfer rate to be an order of magnitude lower. The disagreement is attributed to the poor estimate of the average disturbance-period.

This phenomenon merits special consideration not only because it represents a convection mode that is suppressed under normal gravitational conditions but which is significant at reduced gravity, but also because the oscillatory nature of the force would be expected to reduce the threshold for convection resulting from other forces.

Instrumentation for these experiments needs to be developed to monitor the frequency and amplitude of the varying disturbance. The experiments should first be performed in the usual spacecraft environment with various plane, cylindrical, and spherical containers. With the "background" well established, controlled disturbances of varying frequencies and amplitudes could then be imposed to obtain extensive quantitative data.

Convection Resulting From Electric and Magnetic Fields

Electric and magnetic fields can produce convection and phase separation similar to that generated by a gravitational field. The interaction of charged particles with an electric field (electrophoresis) shows promise for improved separation of biological materials because of the reduction of gravity-induced convection and settling in space. Phenomena such as these have not yet been fully explored or exploited.

Fluid convection can be affected by subjecting a poorly conducting fluid, i. e., an insulator, to a dc electric field and a thermal gradient. Such convection is labeled "electroconvection". The mechanism driving electroconvection results from the fact that the electrical conductivity in insulating liquids is temperature dependent (ref. 59) which produces a gradient of charge density in the liquid. (The change of dielectric constant with temperature is too small to be of any consequence in promoting electroconvection). Electroconvection is reported to increase heat transfer significantly (ref. 60). Discussions regarding the different modes of convection engendered by electric fields are rather confused but, apparently a "wave-front" type of motion is characteristic. Perhaps this confusion is a result of not distinguishing between the relative orientations of the body-force and electrical-conductivity gradients, analogously to the usual gravitational convection wherein density gradients that are normal to the body force or that are parallel and opposed to it lead to different modes of convection. Another kind of fluid motion has been observed in the presence of only an electric field (refs. 60 and 61). This motion is induced in an isothermal, homogeneous fluid by the coupling of ion motion and fluid viscosity (ref. 61).

In earth-bound work the imposed temperature gradient is always vertically oriented to be stabilizing. In space, this restriction is unnecessary and, therefore, a broader range of configurations can be explored. The basic equipment for these experiments would consist of a small glass tank with two opposing sides of aluminum to serve as electrodes and heat transfer surfaces. The test fluid could be corn oil or castor oil. Thermometers or thermocouples could be used and some method of visualizing the flow would

be needed. On earth the voltage required at the onset of motion is of the order of 5 to 10 KV whereas at $10^{-6}g_0$ only about 100 volts would be required. Particular care should be taken to orient the temperature gradient in various directions relative to the electric field and to note the associated different modes of convection. Also an attempt should be made to obtain convection with no temperature gradient, for which voltages of 5 to 10 KV are required. In this case the effect of Joule heating on the process should be carefully assessed.

Electric fields can also produce other convection phenomena. In ref. 62 it was shown that an electric field can produce steady cellular motions in the interface region of two immiscible semi-conducting fluids. The motion depends on the difference in electric conductivity and dielectric constant of the fluids, and on the interface curvature. This motion could be studied in rather simple rectangular channels.

Another mode of fluid motion resulting from an electric field is known as "electro-osmosis", a fluid motion which occurs along a solid wall or capillary surface when an electric field is applied tangentially to the wall and the fluid is an electrolytic solution. The fluid motion arises as a result of the action of the electric field on the charges accumulated at the solid-liquid interfaces. The extent of this region is usually quite small (ref. 62) but the interaction of this flow with others induced by electric fields can be significant.

Electrophoresis is a separation process based on the motion of particles in a fluid resulting from an electric field. Most materials which can be divided into fine particles take on a charge when they are dispersed in an aqueous solution. The charge may be arise from partial ionization, adsorption of ions on the dispersed particles, or ion-pan formation. Particles of different sizes and charges move in an electrified fluid at different velocities, and, hence, separate into distinct zones (ref. 64). Electrophoretic separation is normally characterized by the electrophoretic mobility which is a function of the electric field strength, the particle zeta-potential, the dielectric constant of the fluid, the fluid viscosity, and the shape and size of the particles. Separation is adversely affected by diffusion, sedimentation, and thermal convection. In low-gravity, the sedimentation and thermal convection would be reduced and, therefore, the sharpness of the separation should be improved.

Experiments to demonstrate electrophoresis were conducted during the flights of Apollo 14 (ref. 65) and Apollo 16. The separation resolution and shape of the advancing boundary of separated material was better in space than on earth. In addition, some interesting and unexpected fluid motions were observed which require further study. The so-called

"crescent phenomenon" caused by the simultaneous action of electro-osmosis at the wall and the electrophoretic motion along the axis (ref. 66) was observed. Because the charges on the particles in the fluid frequently have a polarity different from those at the wall surface, the particles move in one direction and the fluid next to the wall moves in the opposite direction. This results in a nose-shaped advancing front. However, in one of the tests in space the front assumed a bullet shape with a "neck" attached to it; this strange behavior has not yet been explained. Also, the measured electrophoretic velocities were much higher than predicted and some turbulent-like motion was observed. Thus, careful experiments are needed to gain more thorough understanding of the individual physical phenomena and their interactions. The experimental equipment can be similar to that used in the previous space flights, and would consist of three test tubes of about 0.6 cm inside diameter and 11 cm length. Electrodes would be located at each end of the tubes with a voltage of 270 volts dc applied to them. Solutions, biological material (hemoglobin and DNA) and mixtures containing polystyrene latex particles can be used as test fluids. The total time to demonstrate the separation is about one hour, during which three specimens could be examined.

Depending on the electrical and magnetic properties of the material under consideration, two types of thermal convection driven by a magnetic field can occur. If the material is an electrical conductor, such as a liquid metal, simultaneous application of a magnetic field and a thermal gradient can cause body forces because of the interaction between the applied and induced magnetic and electric field. In the case of paramagnetic materials that are electrical insulators, simultaneous application of a magnetic field gradient and a temperature gradient can also generate a body force analogous to gravity (ref. 67) because the volumetric susceptibility is temperature dependent. It is shown both theoretically and experimentally in ref. 67 that the magnetic body force can be larger in magnitude than the gravitational body force. To date, however, only the effect of magnetic field gradients on gravity driven currents has been studied. In a reduced-gravity environment the various modes of magnetothermal convection can be identified and described.

Solutal Convection

The more concentrated portions of a solution are of different density than the less concentrated portions. Gravity, therefore, makes the denser portions sink and the less dense portions rise. Inhomogeneous distributions of concentration in an isothermal solution may arise from various causes such as a solid dissolving or precipitating in it. If the concentration gradient is parallel to the gravity vector it is possible to have cellular convection.

Convection generated by concentration gradients alone is rarely important on earth; however, simple experiments which demonstrate pure solutal convection are described in ref. 68. A significant difference between concentration gradients and temperature gradients should be noted: it is theoretically possible to have an initial infinite concentration gradient at the interface between a solution and a pure solvent. An infinite temperature gradient, on the other hand, is unlikely to be of any practical concern because the diffusivity of heat is so much greater than that of the solute. Thus, it is possible for the solutal cellular convection to begin immediately when a heavier solution is placed on a pure solvent. Also, because concentration gradients can be orders of magnitude greater than temperature gradients, gravitational solutal convection could exist even at $10^{-6}g_0$. Experiments to define such flows at reduced gravity are clearly desirable.

As discussed above, surface-tension gradients can cause appreciable convection. The surface-tension gradients themselves can be caused either by thermal or concentration gradients. A practical example of surface-tension induced convection resulting from concentration gradients is the case of a gaseous solute wherein release of gas from the solution by lowering the gas vapor pressure can set up concentration gradients in the liquid surface which would result in surface-tension gradients.

The critical Marangoni numbers for solutal convection observed in the experiments described in ref. 69 are several orders of magnitude larger than those predicted in ref. 57. The theory for solutal convection in ref. 70 provides some rationale for explaining the differences but there are several aspects which require further elucidation by careful experiments.

Thermosolutal Convection

Many unexpected convection phenomena occur as the result of the coupling between thermal and concentration gradients. For example, consider a tank of salty water that is heated from below. The salt concentration initially must decrease with height, for stable stratification. After a time a horizontal cellular structure of convection develops (ref. 71) because heat diffuses faster than solute. Differing diffusion rates for heat and solute also provide an explanation for a number of unusual convective phenomena in solutions. For example, the difference in diffusion rates is held responsible for the salt water convection known as salt fingers (ref. 72). In that case columns of cold fresh water rise and columns of saltier hot water descend. The slow rate of solute diffusion compared to the rate of heat diffusion yields this type of convection even though the mean density field actually decreases with height. Other such unusual situations can be cited.

In addition to the important role of the thermal and solutal diffusivities in thermosolutal convection, temperature gradients can also generate concentration gradients. This is known as the "Soret effect", and its influence on thermosolutal convection has recently come under consideration. The earlier work on thermosolutal convection dealt essentially with heating of initially stratified solutions. From recent work, however, it appears that the influence of the Soret effect has been vastly underrated since it is a natural mechanism by which initially homogeneous solutions can be stratified. Basically, the effect consists of a spontaneous development of a concentration gradient in an initially homogeneous solution when a sustained temperature gradient is imposed. The term "thermal diffusion" is also used to describe the effect but since that is invariably confused with purely thermal or heat diffusion, the term Soret diffusion will be used herein. If mixtures of salt and water, for example, are subjected to a sustained thermal gradient, salt migrates towards the cold end and increases the concentration gradient there. This is somewhat surprising because it would, offhand, be expected that the concentration gradient would develop in the direction of greater solubility, i. e., salt is more soluble in hot water than in cold. Therefore, a greater concentration of salt in the warmer regions would be expected on that basis. In any case, a general rule of thumb is that the heavier components generally migrate toward the colder regions and the lighter components toward the warmer regions.

The inverse of the Soret effect is the Dufour effect, i. e., a concentration gradient generates a temperature gradient. This effect is important only for gases.

The Soret effect has been used in various separation processes, but is not very efficient because, in the absence of convection, back-diffusion is significant. Convection overcomes the effect of back-diffusion markedly so that the separation process becomes more efficient by orders of magnitude. This method has been used to separate isotopes and variety of mixtures, including oils, organic isomers, electrolytes, and biologicals. However, in a normal gravitational environment the annular column spaces have to be very narrow to inhibit the convection which would otherwise be turbulent and harmful, and this results in small batch samples and large power requirements. The advantage of Soret separations in reduced-gravity environments is that larger sample sizes can be attained (more than 30 times as large at $10^{-6}g_0$) while still maintaining the desired laminar convection; that is, the low-gravity environment is utilized to control rather than eliminate convection. Also, in the space environment no electrical power is required since solar radiation can be used.

To gain an understanding of these unusual phenomena, it is proposed that a series of experiments be conducted to delineate the many flow and transfer processes that occur when temperature and concentration gradients exist simultaneously. Depending on the relative directions of the density and temperature gradients and the direction of the gravity vector, a given configuration and solution may or not be prone to convection. Furthermore, numerous convection modes are possible.

Most existing work is related to configurations in which the gradients are aligned with the gravity vector, either opposed to it or in the same direction. In future experiments they should also be transverse to the gravity vector. The convection patterns should be determined and the degree of separation determined. Ethanol-water solutions and annular gaps on the order of 1 cm to 3 cm can be used.

Convection Driven By Gradients In Chemical Potential

Reference 73 established the possibility of generating fluid motion without body forces by mechanochemical means in a continuous material having an appropriate subcontinuum structure. One very well known example of such a motion is that driven by interfacial-tension (Marangoni effect). Several cases of stationary instability with respect to small disturbances are given in ref. 73: active antisymmetric or deviatoric stresses that are linear in concentration gradient and effectively anisotropic in radial geometry, with a radially weighted bias; and active antisymmetric or deviatoric stresses that are isotropic and bilinear in a pair of concentration gradients. In the case of antisymmetric stress, strong evidence was found for an oscillatory instability. The source of kinetic energy imparted to the flow and driving the oscillations is the chemical energy that is transformed to concentration-dependent free energy by the reaction process responsible for the initial concentration gradients.

The results presented in ref. 73 indicate that if a material exists in which the passive stress is Newtonian and in which there is an active stress that depends nonlinearly on temperature or concentration, it should be possible to induce motion in the material by imposing a sufficiently large gradient. It is postulated that convective instability by active stress causes some biological phenomena and that there is a need for appreciation of states of stress other than isotropic bulk pressure and one-dimensional contractile force. Motion that sets in suddenly and spontaneously in fluid or material at rest without body forces represents conversion of internal energy directly to kinetic energy. There are indications that such mechanisms operate at the cellular level in living systems and possible elsewhere. Reference 73 has established what type of mechanisms could generate such motions. Here are many challenges to theoretical rheology, plasticity and fluid mechanics.

Convective instability by active stress has not heretofore been observed, except possibly in biological systems. The reason for not seeing such phenomenon is probably that it has been masked by gravitational effects. Low-gravity will allow strong temperature gradients to be applied without convection induced by gravity. It will, therefore, seem worthwhile to investigate the generation of fluid motion by self-starting, continuous mechanochemistry in mechanically isolated systems without body forces.

A study must be first conducted to establish candidate fluids and chemistry. Polymeric and colloidal systems have been suggested as approximating living protoplasm. At low-gravity there ought to be several candidates. One could select suitable osmotic membranes and utilize reactions similar to those occurring in fluidized photosynthetic processes. In any event, the apparatus would be of moderate size (0.1 m^3) and the experimental measurements required would be relatively simple. The experimental procedure would be the same as for the thermal stability experiments.

Coupling Phenomena

When two or more driving forces for fluid flow are operative in a given fluid, their combined action may be such that a given mode of convection is reinforced, annulled, or altered. In a sense, thermosolutal phenomena and electroconvection with temperature gradients are examples. What little work has been done on problems of this type pertains to very specific fluid configurations and the results are not readily generalized or predictable. The combined effects of gravity and surface tension and of gravity and rotational acceleration fields in cellular convection have been analyzed, and recently on Skylab 4 the combined effects of centrifugal force and surface tension were observed experimentally. In the Skylab tests, the spin-up of a freely-floating water bubble led to a dumbbell shape which eventually broke up into two separate bubbles. It would be extremely interesting to determine the internal flows in such a changing configuration. Another experiment conducted on Skylab 4 in which surface tension and centrifugal forces interacted involved a free liquid-cylinder attached at each end to rods that could rotate. With the rods both rotating in the same direction and after a critical rate was attained, the liquid zone assumed a "jump rope" instability, i. e., it appeared like the letter U which rotated about its end. This motion damped out rather quickly when the rotation ceased. Axisymmetric (bottle-like) instabilities are also possible. For more complete experiments, the material at the end of the rods should be varied to give different wettabilities. The liquids should also have different surface tensions in order that its effect on the rotation rate for zone breakup can be assessed. Again internal flows should also be determined.

The various methods of crystal growing from the gas phase, from solutions, and from melts are other examples of coupling of convective driving forces. Nucleation, homogeneity, and microstructure depend on the convection. Furthermore, most measured crystal growth rates are larger than those predicted on the basis of pure diffusion. Convection evidently must increase the concentration near the crystal. Most of the crystals grown on space flights seemed to be better in all regards than similar ones grown on earth. Thus, the coupling phenomena in space seem to be different and should be explored in depth. One such experiment in which significant convection would arise from surface tension and solutal motion is the precipitation of crystals of Rochelle salt (double tartrate of sodium and potassium) from a saturated solution. Rochelle salt is an extensively studied, non-hazardous, ferroelectric crystal, with a solubility curve that is suitable for room-temperature operation. A cylindrical container about 10 cm in diameter can be filled with the saturated solution, Rochelle salt powder, and a small seed crystal. The container will then be heated (at about 65°C) until the crystal is nearly all dissolved. The container would then be removed from the heater and insulated so that it cools slowly to allow the crystal to regrow. The convective currents should be measured during both the heating and cooling phases.

Thermally Unstable Flows

When a fluid is heated from below, a complex cellular flow is established at some critical value of the Rayleigh number (a comparison of gravity-driven convection and pure conduction). Such flows are encountered in technology as well as in meteorology and other geophysical areas, and are the simplest kinds with which to study the fundamental mechanisms of the transition to turbulence. Thus far, only gross characteristics have been measured. Detailed and accurate measurements of velocity and temperature fields would further the understanding of such flows. The cellular flow undergoes a transition to a new flow at about 10 to 15 times the critical Rayleigh number, which is the beginning of the transition to turbulence. Fully turbulent flow is attained at 200 to 300 times the critical Rayleigh number. Earth-based experiments are of relatively small scale so that accurate, detailed information is extremely difficult to obtain. But if gravity were reduced by four orders of magnitude, for example, the product of the cube of the characteristic length and the temperature difference (numerator of Rayleigh number) could be increased by the same amount. Thus, the length could be 21 times greater than in the earth laboratory for the same temperature difference and fluid, or the temperature difference and characteristic length could each be an order of magnitude larger. For the latter case the influence of fluid property variations with temperature could be studied.

An experiment is proposed to obtain detailed measurements of the thermal and velocity fields in a fluid heated from below, for Rayleigh numbers from critical to 300 times critical, and to establish the structure of the transition to turbulent flow. The test chamber should consist of two parallel plane surfaces at least 0.6 m x 0.6 m, and the spacing between them should be variable from several centimeters up to 30 cm. A power capability of 2 KW would be more than sufficient. A timer, TV or motion picture camera, heat flux meters, hot wire anemometers and various instruments for temperature and pressure measurements are needed. Holographic interferometry is desirable for temperature measurement. The experiment would be carried out by filling the apparatus with some pre-selected fluid and adjusting the heating and cooling to desired levels. Measurements would then be made after steady state has been attained.

Non-Heated Multiphase Mixtures

A number of experiments involving multiphase mixtures are recommended. For convenience in the presentation, these experiments are discussed in two groups: multiphase phenomena with no heat transfer, and multiphase heat transfer, which is treated in the next section.

On earth, multiphase mixtures generally segregate or separate because of differences in density. In the absence of gravity, dispersions and foams are formed more readily and are more stable with respect to segregation and separation. Such ease of formation and stability may be advantageous or deleterious for different processes depending on their objectives. The Space Shuttle offers an opportunity to study the factors controlling the formation and stability of multiphase mixtures without the complication of gravity, and the opportunity to carry out fundamental experiments with multiphase mixtures which cannot be carried out on earth because of separation. Dispersions of liquid and solid in gas, in liquid, and liquid in liquid will be considered in turn. Some experiments on bubble dynamics are also discussed.

Mechanics of Aerosols

Aerosols coalesce and settle as a consequence of collisions, surface charges, surface tension, and gravity. In low-gravity, convection is eliminated or reduced drastically, thereby reducing the frequency and intensity of collisions. On the other hand the reduction of shear forces reduces the disruption of chains of particles, such as soot. In any event the absence of gravity eliminates settling except as resulting from other field forces, and aerosols should be much more long-lasting and uniform.

The characteristics and behavior of aerosols in low-gravity are of intrinsic interest, and the persistence of dispersed liquids and solids in the atmosphere of a space vehicle may be either desirable or undesirable from the health and safety.

Experiments are proposed to determine the long-term size-distribution and stability of dispersions of liquids and solids in air in low-gravity. Dispersions of liquids and solids in gas can readily be generated in a test chamber in the space vehicle by spraying. Soot can be generated by combustion with insufficient air. The particle density and size-distribution can be measured at a series of times by light transmission and scattering, the principal apparatus required consisting of a collimated source of monochromatic illumination, preferably a laser beam, at one or more frequencies, and a calibrated photocell which can be mounted and automated to sweep through at least 90° of angle. The general method of measurement has been described in ref. 74, and previously developed apparatus for soot generation and measurement may be a useful guide. Provision should be made for cleaning out the experimental chamber between experiments.

Foam Formation, Stability, and Behavior

Foams are destroyed by gravity and surface tension. In low-gravity, uniform foams should be easier to form and maintain. Hence it may be possible to construct unique metal or plastic structures by foaming and freezing in space. It should also be possible to study the fundamental characteristics of foams under more controlled and stable conditions than on earth and to observe the fundamental role of surface forces in the absence of the complication of gravity.

Experiments are suggested in which liquids are first foamed and then solidified. The foaming may be carried out by injection of gas into a flowing stream of liquid, followed by mechanical agitation to achieve isotropy and perhaps a controlled size of bubbles. The foam can be solidified by cooling and freezing or perhaps by chemical reaction (in the case of a polymer). Metal foams are probably of greatest practical interest but preliminary experiments with paraffin may be justifiable on the basis of experimental simplicity and safety. Water-gas foams can be generated similarly and the viscosity and stability tested by pumping the foam through a capillary tube. The effect of surfactants can be tested in repeated experiments.

These experiments require metering of the gas and liquid. The gas can be supplied from a pressurized source and the liquid either from a pressurized source or by pumping, in which case the pump may serve as a meter. Light-scattering equipment, as described for the aerosol experiments, is necessary to measure the density and bubble-size-distribution for the water-air mixtures. These characteristics may be measured on earth for the frozen samples if they can be returned undamaged. The density can be determined in space by volume-

tric and inertial measurements. A differential-pressure detector and a flow meter are needed to measure viscosity. References 75, 76, and 77 provide background for these experiments.

Liquid-Liquid Dispersions

Liquid-liquid dispersions have many applications such as for extraction and for the controlled flow of mixtures of immiscible fluids, e. g. water and oil to engines. Such dispersions are generally destroyed rapidly by gravity, hence they are difficult to generate and even harder to study, in any fundamental sense, on earth. In low-gravity the generation of uniform dispersions and their maintenance should be much easier, offering an opportunity for study of their fundamental characteristics.

Experiments are suggested in which liquid-liquid dispersions are generated by agitation of previously weighed quantities of the two liquids in a closed container. The drop-size distribution and long-time stability can be determined by light-scattering as described for aerosols. The viscosity can be determined either from the power required by a rotary or vibrating device or by pumping the fluid through a tube as described below. The effect of surfactants can be determined in repeated experiments. Agitation can be accomplished by stirring or shaking.

Liquid-liquid dispersions can also be generated by pumping or pressuring the two liquids through a tube containing glass spheres as described in ref. 78. The density can be determined by metering the two input streams, the drop-size distribution and long-term stability by light scattering, and the viscosity by measuring the pressure drop in flow through a capillary tube. Again the effect of surfactants can be studied by repeating these experiments. Related experiments are described in refs. 79 and 80.

Dynamics of Bubbles

The dynamics of bubbles in liquids in low-gravity have been explored heretofore only cursorily. Many interesting phenomena are known to occur, and a large number of worthwhile experiments could be proposed. Only a few of these are discussed here.

A single, non-condensable gas bubble moves in a straight vertical line when it is spherical and has a Reynolds number less than several hundred. For higher Reynolds numbers, the bubble is distorted and moves in a helical or zig-zag path. In low-gravity, the bubble size can be much larger before the unstable, non-rectilinear motion starts. Understanding the types of bubble motion that are possible in low-gravity is important in spacecraft design, and therefore experiments are proposed to study the motions in the space laboratory. The interaction

of a bubble with a surface, especially a liquid free-surface, is also a fruitful field for study in space. Here it is proposed to determine the types of bubble motion that occur in the vicinity of a solid wall, and the magnitude of bubble velocity, size, and buoyancy force needed to cause the bubble to break through a free-surface, i. e., vent. Experiments are also proposed to observe the way in which several bubbles coalesce. The extended test times made possible by low-gravity will allow detailed study of the bubble rupture and coalescence processes. Further, larger bubbles can be used without loss of sphericity.

The apparatus needed for these experiments would be moderately large containers (say, 50 cm. in diameter) with provisions for inserting gas or vapor bubbles at various locations. The test fluids should cover a wide range of viscosity and surface tension. Variable gravity levels are required, so some of the tests must be conducted during low-gravity thrusting. Most of the observations could be made visually with high-speed photography. Ground-based analyses and tests would obviously be beneficial to aid in defining these experiments.

Multiphase Heat Transfer

The relatively long periods of low-gravity provided by a space laboratory, as well as access to the space environment, are needed to obtain a better understanding of the effect of low-gravity on boiling, condensation and other multiphase heat transfer processes. Therefore, several types of experiments are proposed. The detail with which each experiment is defined is partly a measure of how much attention has been paid to a particular subject in the past. For example, pool boiling has been studied extensively in low-gravity earth-based experiments. As a result, space experiments in this area will be used to expand the previous work, taking advantage of the extended low-gravity periods. This is also somewhat true of forced-flow condensation experiments. On the other hand, the small amount of low-gravity testing in forced convection boiling have only indicated that some unexpected phenomena may be present. As a result, the proposed tests are not defined in as much detail and the first step will likely be to cover a range of experimental conditions to bracket the problem and to identify flow situations that are gravity dependent. Evaporation and condensation from augmented surfaces, can also benefit from study at low-gravity conditions by obtaining a more fundamental understanding of these processes at gas-liquid interfaces. In particular, it would be valuable to determine how they are affected by fluid and thermal properties, gas-phase characteristics, the wettability of a heated surface, and the surface geometry near the interface.

The rapid cooling of molten metals can be considered in a separate category. Here the goal is to utilize the space environment to see whether or not significant improvements can be made in the production of certain alloys.

Boiling Heat Transfer

Although boiling heat transfer is one of the most efficient means of heat removal, the various boiling regimes are not entirely understood. Theoretical analyses are available for peak heat flux and film boiling situations. Droptower and aircraft results indicate some agreement with theory in this area; however, lower gravity levels and longer test periods are required to make an adequate comparison. The transition region between the nucleate and film boiling regimes has not been modeled and consequently little information on how this regime is affected by gravity is available. The same is also true for the incipient boiling point as a function of gravity. Finally, nearly all of the existing nucleate boiling models and correlations show a gravity dependence which have been inconsistent with the present low- and high-g data. As a result, further experimental clarification of the low gravity effect on boiling is needed.

The availability of an extended low-gravity period offers the opportunity to achieve several objectives. One is to obtain a correlating equation for the boiling heat transfer coefficient as a function of the magnitude of the gravity field. The other is to obtain visual data for the bubble growth and removal phenomena which should contribute to the understanding of the mechanism. The successful synthesis of results from both categories should result in a more complete quantitative description of boiling as a function of gravity. Much of the apparatus and instrumentation for these experiments is common to both.

Effect of Gravity on the Boiling Curve. - The main objective of this experiment is to determine the effect of low-gravity on each of the regimes associated with pool boiling heat transfer from heater surface. These regimes include incipient boiling, nucleate boiling, peak flux, transition boiling, and film boiling, which are illustrated in fig. 4 for a 1-g₀ condition. The heater surface-temperature would be measured as a function of the wall heat flux for a given liquid, gravity level, and heater surface. A photographic analysis of the bubble phenomena would be an integral part of this study and can be accomplished with a high speed motion picture camera and the appropriate lighting.

Since the scope of this experiment could easily exceed the capabilities of the laboratory for any single mission, it will be necessary to make a priority rating of the individual experiments and fit them within the available resources. Some of the parameters in addition to gravity level that should be considered are subcooling, heater surface orientation, heater size, surface conditions, and liquid properties.

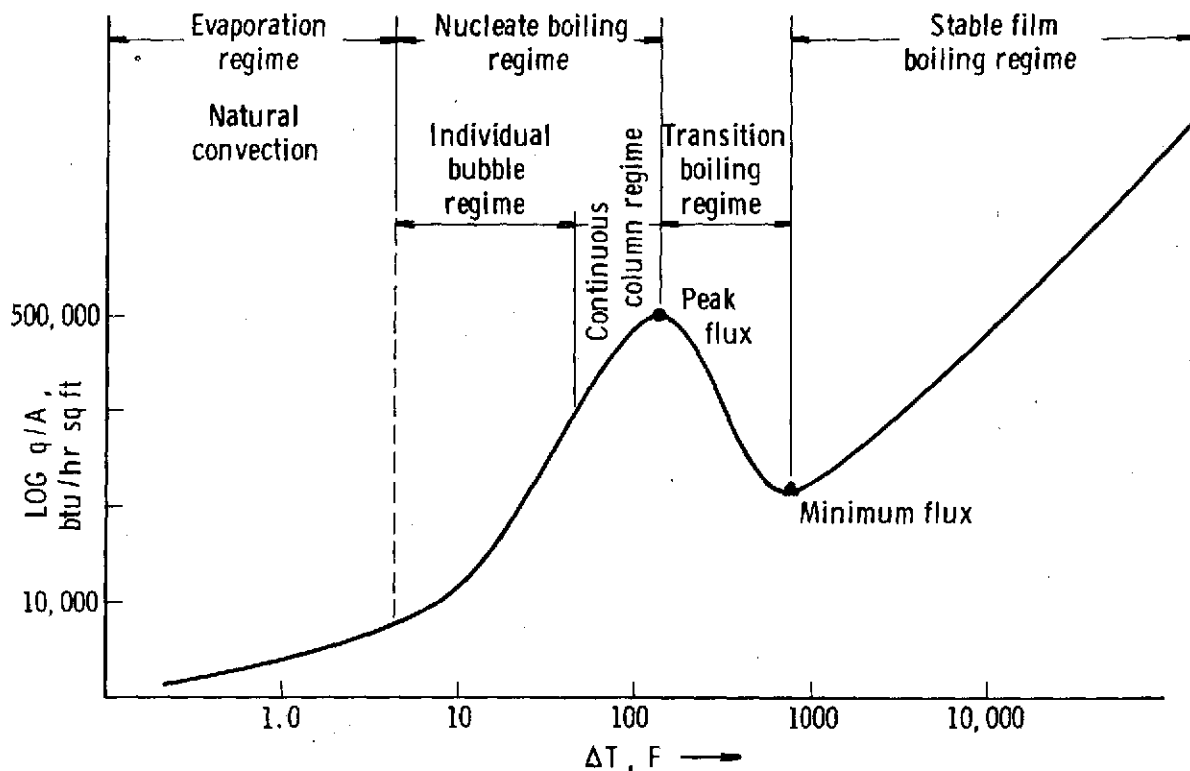


Figure 4. Typical boiling curve for water under 1-g₀ conditions

Descriptions of boiling apparatus available in the literature can serve as a guide for this particular experiment. Reference 1 presents an earlier design of a low-gravity boiling experiment that may be especially useful. The simple technique of placing a heated body into the liquid and recording its heat loss rate and temperature as it cools could be employed if necessary (ref. 81). The major equipment, such as the outer test tank, the lighting and camera, and much of the instrumentation should be common to all of the boiling experiments. The test heaters most likely will differ, and the system should be designed to allow for easy installation and removal of heaters between experiments. The size and shape of the heater surface will have to be carefully considered, and

more than one geometry and size should be used, depending on the laboratory mission constraints and priorities. An important consideration in this regard is the study reported in ref. 82 in which the interacting effects of gravity and heater size on the peak and minimum heat fluxes for pool boiling were studied. These results indicate that when the ratio of the buoyancy forces to surface tension forces becomes small, a boiling regime is reached that differs appreciably from the conventional one. Here the distinct maximum and minimum fluxes (see figure 4) as well as the nucleate boiling domain tend to disappear. Hence, the experiments should be conducted to extend results in this regime as well as in the regime where a conventional boiling curve is expected. If the observations of ref. 82 hold at low gravity values, heater sizes will have to be increased considerably over those used at $1-g_0$ in order to obtain the conventional boiling regime. Reference 83 has also pointed out the need for considering larger heaters for low-gravity boiling.

The temperature of the liquid and the heater surface must be measured. If the added complexity is still within practical limits, a small, moveable probe could be used to measure the large temperature gradient in the liquid close to the surface of the heater. Thermocouples can be used for all other temperature measurements, although liquid crystals may be an alternative if simplicity is required.

Several different levels of complexity can be designed for recording the bubble phenomena. The simplest would be to use a high-speed motion picture camera with the proper lighting, while a somewhat more complex arrangement would use a shadowgraph or Schlieren system in conjunction with the high-speed camera. This type of photography would provide information on the transient formation and disruption of the thermal layer adjacent to the surface of the heater.

The total energy requirements and the test period will depend on the actual number of experiments that are conducted. For a given heater, liquid state, and gravity level, approximately 25 data points should cover the entire boiling curve. This would require on the order of 8 hours to complete. In addition, at least 3 gravity levels should be employed. The maximum power requirement would be of the order of 5 KW and the total energy requirement for a single boiling curve would be between 0.5 and 5.0 KW hours. Thus, for a single liquid and heater, if 3 gravity levels were available, for example, the total test period would be approximately 25 to 30 hours. The total energy requirement will be less than 15 KW hours for the heaters plus approximately 10 KW hours for camera lights. The degree of manual operation for this experiment can be small or large, depending on the design. The major control tasks will include

heater adjustments, camera and lighting adjustments, and temperature and pressure controls. These could all be automatically sequenced or carried out by an operator. Reference 84 presents a method of feedback control that can produce the entire boiling curve without danger of burnout. Nevertheless, there are certain tasks which will require manual operation.

Bubble Forces. - Steady nucleate boiling can occur only as long as there is a continual removal of the bubbles formed at the surface. The magnitudes of the various bubble-removal forces depend on both the liquid properties and the physical conditions. A study of the forces associated with bubble attachment, growth, and breakoff in low-gravity will provide a more fundamental and quantitative understanding of how gravity affects the nucleate boiling process.

The object of this particular experiment is to record the bubble-size visually as a function of time, which will then be used to calculate the magnitudes of the bubble forces. Figure 5 is an example of the curves that can be obtained.

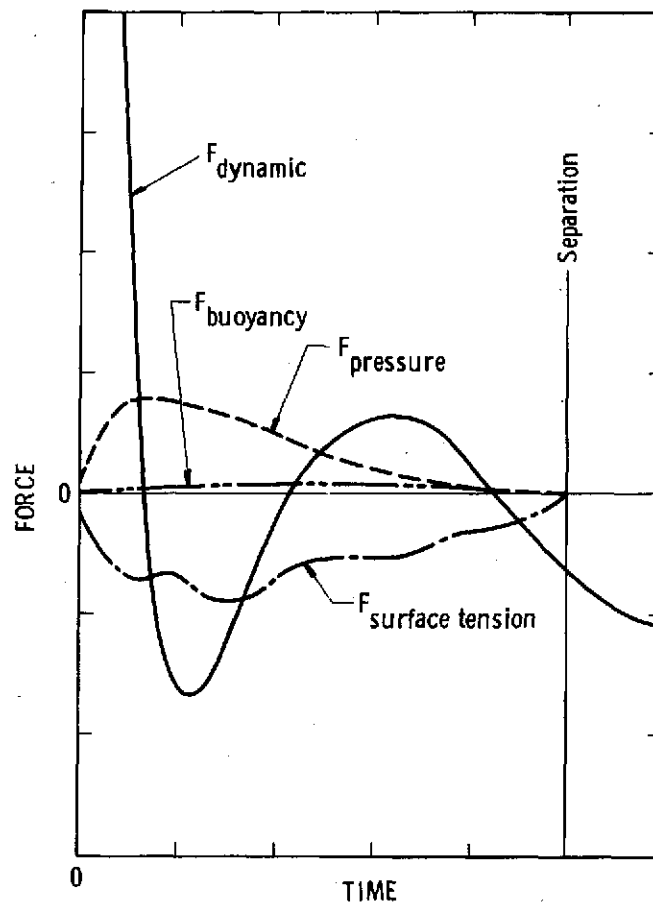


Figure 5. Force-time plot for a low gravity bubble

Various liquids will be used to investigate the effect of changing the order of importance of the various parameters affecting the bubble forces. This set of experiments would essentially be an extension of earlier droptower tests (refs. 85, 86, and 87) which showed that bubble-departure was governed by the interaction of the buoyancy, inertial, and surface-tension forces. Liquids which resulted in rapidly growing bubbles demonstrated that the inertial effects could play a more important role than buoyancy in removing bubbles in low-gravity. An orbiting laboratory will allow the parameterization of heat flux values and gravity levels over considerably longer test periods and also eliminate any possible transient effects which may have occurred in droptower tests. Liquids should be used that would cover a wide range of values of the force ratios. It should be possible to verify whether or not the breakoff diameter of bubbles can be correlated with these force ratios. The results should also be examined with respect to the relationship between overall heat transfer and gravity.

The basic difference in apparatus between this experiment and the one to obtain boiling curves is in the heater surface. Since the number of natural nucleating sites must be small in the bubble forces study, a highly polished surface should be used. However, it may be possible to design the heater systems so that they are interchangeable or a smooth surface could be added for this set of experiments. The photographic arrangement would also be the same although it may be necessary to increase the camera speed for these experiments. Energy and time requirements would be of the same order as those for the boiling curve experiments. Although fewer data points will be needed for a given liquid, a larger number of liquids should be used. Experiment control criteria should apply in approximately the same way for both the boiling-curve and the bubble-force experiments.

Bubble Microlayer. - Present evidence suggests that the microlayer which forms at the base of growing bubbles is the dominant mechanism of the bubble growth and also may be the major contributor to the heat removal process. A sketch of the microlayer is shown in figure 6. For some fluids there will be an extended time period of bubble growth in low-gravity that can be used to provide a more accurate determination of this effect. The time history for a microlayer may be easier to measure than for small bubbles. These data can then be related to the overall boiling mechanism (boiling curve) at various low-gravity levels to compare the relative importance of microlayer evaporation and bubble agitation as mechanisms of heat removal. If this can be experimentally resolved, a better basis will be provided for developing a model of nucleate boiling.

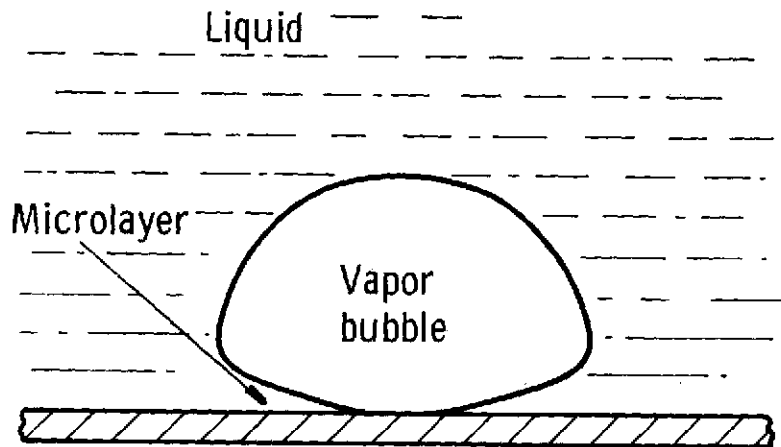


Figure 6. Bubble microlayer

The objective of this experiment will be to determine the geometry of the bubble microlayer attached to the heater surface. Reference 88 may serve as a guide for the design of the low-gravity optical system. An indirect method of determining the effect of microlayer evaporation on boiling may be considered as an alternative or as a second experiment in this area; references 89, 90, and 91 indicate different approaches.

High-speed, interferometric, motion-picture photography from beneath a transparent heater surface has already been employed (ref. 88) to provide the details of microlayer geometry. Here, the heater was a glass disc coated with an electrically conducting, transparent film of stannioxide; vertical glass walls enclosed the heater bottom and provided the boiling container, which was immersed in a second tank. The water jacket in the second tank controlled the bulk temperature within the boiling container. The test period and heater power for the microlayer experiment should be less than that for the boiling-curve and bubble-force experiments. It is unlikely that this experiment can be automated because of the complex optical system required.

The Marangoni Effect on Bubbles

A limited amount of work has gone into investigating the liquid motion in the vicinity of a gas or vapor bubble resulting from a temperature gradient within the liquid. In general, surface tension decreases with increasing temperature and thus is greater in the cooler region surrounding the bubble. In addition to the Marangoni flow, a bubble within a temperature gradient will experience a force unbalance, which, however, is overshadowed by the buoyancy force in earth-based experiments and is difficult to measure. Accurate measurements of this effect therefore must be obtained in a low-gravity field. The Marangoni flow near a bubble attached to a heater surface may also be important as a heat transfer mechanism (refs. 92, 93, and 94) although experimental results are not definitive, which may in part be caused by buoyancy forces present on earth. Since the convection heat-transfer mechanism will be significantly reduced in low gravity, the Marangoni effect should be readily observed in space by placing one or more bubbles on a heated surface and comparing results with and without the bubbles.

In low-gravity, the location of the liquid and vapor phases in a container may not be known with certainty. If the Marangoni effect results in motion of an unattached bubble, then in a liquid with a temperature gradient the bubbles should migrate towards the hottest wall. If the magnitude of this effect and the gravity domain where it is important can be established, the rate of bubble migration and the prediction of their ultimate destination can be made.

Experiments in low-gravity are proposed to determine whether the Marangoni effect can cause an unattached bubble to move through a liquid, and to determine the magnitude of the effect on heat transfer from a surface. The apparatus could consist of a transparent, cylindrical tube with an electrical heater at one end. Provisions would be made to insert a bubble into the tube at several locations along the tube, including the heater surface. The longitudinal axis of the cylinder would be oriented in the same direction as the gravity vector.

The experiments on attached bubbles should be conducted with the heater surface facing both "upward" and "downward" with respect to the gravity vector. One or more bubbles will be attached to the surface for both cases. The resulting effect on heat transfer because of the induced motion of the liquid near the bubbles can be obtained by comparing these results for both heater orientations without bubbles. The heater temperature for a given heat flux should be measured for all cases, and visual observations should be made. The flow patterns can be obtained by photographing the motion of small particles placed near the heater or by shadowgraph and Schlieren photography. The study of bubble motions can be conducted with the same

apparatus by inserting the bubble into the tube at some distance from the heater surface, again with the heater surface oriented in both directions. A third case should also be conducted with the heater off so that the bubble motion in an isothermal environment can be measured. In this manner, the effect of the temperature gradient on the bubble motion can be determined. For both of the experiments, tests should be conducted with several liquids having widely varying surface tension - temperature relationships and by parameterizing both the temperature gradient and the gravity field. Requirements for the heater size must be considered in designing the experiments.

Field Effects on Boiling

A space laboratory can also provide the conditions with which to study the effect of electric, magnetic, and acoustic fields on boiling heat transfer. As with the convection experiments, the low-gravity lets the effects of these fields be isolated from the gravitational effect. These experiments can be included within the framework defined for the low-gravity boiling experiments. Thus, boiling curves and bubble-phenomena data can be obtained as functions of the various field strength under low - gravity conditions.

The proposed experiments will require instrumentation common to both the boiling and the convection heat transfer (with fields) experiments, so it should be possible to conduct these experiments with some of the apparatus and instrumentation from each. It is also likely that the containers and the heating elements from the boiling experiments can be used.

Forced Convection Boiling

When flow rates in forced convection boiling are sufficiently high, the pressure and drag on the bubbles may be considerably larger than the buoyancy forces. In this regime, the effect of gravity on heat transfer is not generally considered to be important. As a result, relatively little attention has been paid to the effect of low-gravity on forced convection boiling. Nevertheless a limited number of short duration experiments have been carried out and some unexpected results have been observed. For example, an instability has been found that only occurs in low-gravity (ref. 95). The flow was intentionally interrupted while heating of the tube was continued, and, when the flow was restarted, it was not steady. It was postulated that in low-gravity the bubbles coalesced during the period of no flow to form large vapor masses and liquid slugs, thus altering the liquid-vapor flow characteristics. This did not happen at $1-g_0$, since buoyancy forces in the

no-flow condition separated the liquid and vapor differently. In addition, ref. 96 reported that pressure oscillations in a heated flow loop were significantly damped in low-gravity but not at $1-g_0$.

These two examples illustrate that there are differences in heat transfer and flow between $1-g_0$ and low-gravity for forced convection boiling, and that there is a need to define those flow regimes which are gravity-dependent. Both transient flow and the steady state must be considered. An analysis of bubble forces will aid in defining the limits between gravity-dependent and gravity-independent flow regimes. In addition, critical heat flux values for various gravity levels and various flows orientations with respect to gravity can be determined experimentally as a function of the important flow parameters using an approach similar to that of ref. 97 at $1-g_0$.

These proposed experiments on forced convection boiling may be incorporated into the flow loop for the experiments on forced convection condensation described below.

Forced Flow Condensation in Tubes

Conventional vapor condensation methods are inefficient in low-gravity because of their dependence on body forces to help drive the condensed-liquid flow. A proposed method of continuously condensing vapor under low-g conditions is to pump the vapor inside cooled tubes. A liquid-vapor interface is formed somewhere in each tube, across which the phase change occurs in the presence of an overall mass flow. The interface must remain stable for the scheme to work and the conditions for stability are not well understood. Previous experiments (refs. 98 and 99) with small horizontal tubes at $1-g_0$ have shown the total pressure of the vapor must be controlled accurately in order to make the pressure drop in the tube compatible with the pressure jump across the interface caused by capillary forces, or else the interface translates up or down-stream. It also seems that the jump in fluid density across the interface leads to a jump in fluid velocity, and the forces produced by the momentum change may cause instabilities. When high vapor flow rates are used, droplets formed upstream will strike the interface and cause oscillations or dislodgement; thus, there probably is an upper limit on the rate of condensation for a given tube diameter and given fluid properties. Therefore, experiments in low-gravity, where much larger tube diameters can be used because of the absence of potentially destabilizing body forces, would be valuable to survey the interfacial stability of various wetting and non-wetting liquids as a function of flow rate, total pressure, contact angle, interfacial tension, tube diameter, etc.

In addition, the problem of liquid runback which will occur upstream of the interface can produce instabilities. Reference 100, which gives an analysis of an orbital experiment on condensing heat transfer experiment, may be useful during the design phase of the experiments. Finally, as suggested in ref. 99, two-phase forced-flow experiments should cover a wider range of flow and heating variables than have been covered to date. These, along with some transient flow conditions, should be studied to determine whether or not any other significant effects of gravity may be found.

Evaporation and Condensation from Augmented Surfaces

Where there is a change of phase, devices for augmenting heat transfer can give significant savings in capital and energy costs. Sea water conversion, for example, requires evaporator tubes for which the evaporation can be increased by surface tension through proper shaping of the tubes. The process for liquefying natural gas requires heat transfer at very small temperature differences to be economical; the condensing side is controlling, and surface tension control by shaping of the tubes is currently used. In these applications, most of the heat transfer occurs at a meniscus, and, at present, enhancement of heat transfer by surface tension effects is not well understood. Measurements on earth are very difficult because the meniscus is so small, and flow within the meniscus is inferred rather than measured. Low-gravity permits a much larger geometric scale.

A shaped, heated (or cooled) surface will be placed in an environmental chamber, with sufficient instrumentation to measure heat flux. During an evaporation experiment, vapor will be removed from the system and liquid added, whereas during a condensation experiment vapor will be added and liquid removed. Photography and holographic interferometry can be used to determine the shape of the vapor-liquid interface and the temperature distributions in the meniscus and in the nucleating bubbles. If possible, the apparatus should be designed so that electric and acoustic fields can be investigated. Dropwise condensation is of particular interest.

Solidification and Cooling by Liquid Impingement

The study of rapid cooling by a liquid impinging on a solid surface has been studied to a limited extent (refs. 101, 102, 103, and 104). The name "splat" has been given to alloys that have been cooled from the molten state so rapidly that they solidify in a metastable state. Splat, in addition to having some unusual mechanical characteristics, also has interesting electrical properties. The technique has been used to identify superconductors, although other methods are used to produce significant quantities of the material. Splat has also been used to make amorphous ferromagnetic alloys.

The classical approach to cooling solid alloys rapidly enough to freeze in metastable phases is by forced convection. Heat transfer can be greatly increased by using a velocity of several hundred feet per second for the cooling fluid in contact with the specimen, by using fluids which have a high thermal conductivity such as hydrogen or helium, and by utilizing specimens about 50 microns thick and a few millimeters in diameter. Such techniques can produce cooling on the order of 10,000 to 20,000 C°/sec. To obtain higher rates of cooling, the heat-removal mechanism must be conduction. High rates of cooling by conduction require that the substrate must be made of a good heat conductor; very good thermal contact must exist between the liquid and the substrate; the liquid layer must be relatively thin; and the time between initial contact of liquid with substrate and the end of solidification must be extremely short.

The three methods of producing splat on earth—the shock gun, the plasma jet, and the anvil and hammer—all suffer from serious shortcomings which might be overcome by a space-production technique. A space laboratory offers at least two advantages in studying splat: (1) a hard vacuum, which would reduce the possibility of contamination of the resulting alloys; and (2) a good heat sink for maintaining the substrate at a low temperature.

The proposed experiments for space are ones designed to learn more about the materials produced by rapid cooling of metal-alloys as well as the mechanism of high rates of heat transfer. The apparatus used to carry out the experiments might consist of a crucible for melting the material to be splatted, a method of pressurizing the crucible, and a copper or some other high-conductivity material substrate, so arranged that one side can be directly exposed to space. The chamber in which the experiment is carried out should be equipped for venting to space. Splat is then produced by forcing a quantity of molten material under pressure out of a nozzle on the crucible onto the cold substrate while the whole apparatus is exposed to the hard vacuum of space and one side of the substrate is exposed to the low temperature of space with an appropriate heat removal system.

EFFECTS OF A SPACE LABORATORY ENVIRONMENT

The environmental effects of a space laboratory must all be considered in designing an experiment and interpreting the data. Failure to do so can compromise the intended objective or even lead to erroneous conclusions. The most important of these effects are discussed in a general way in this chapter.

Non-Uniformity of Gravity Field

Many of the proposed experiments require only that the gravitational field of the space laboratory be so small that gravity forces are negligible with respect to other forces, i. e., the absolute magnitude and orientation of the gravity vector is irrelevant, as are small non-uniformities. Experiments on free-surface dynamics and capillarity are typical of this class. For container sizes commonly used in experiments, surface-tension forces will be many times larger than gravity forces whenever $g \lesssim 10^{-5} g_0$ or even $g \lesssim 10^{-4} g_0$, and hence, non-uniformities in g of this magnitude or smaller are inconsequential. The critical phenomena experiments are also in this class. For other experiments, typified by the convection groups, it is probably necessary not only that $g \lesssim 10^{-5} g_0$ or $10^{-6} g_0$ but also that gravity acts uniformly and constantly on the whole experiment. To put these possible effects into perspective, several causes of non-uniformity must be considered.

A vehicle in orbit is in equilibrium with two forces. The centrifugal and gravitational forces balance at the vehicular center of gravity. Away from the center of gravity, the gravitational acceleration is directed normal to the vehicle's trajectory; outside the center of gravity, the force is directed outwardly and inside it is directed inwardly (towards earth). A simple force balance, ignoring small terms, gives the following relation for the perturbing acceleration:

$$a \approx \left[\Omega^2 + \frac{2 g_0 r_0^2}{(r_0 + \delta r)^3} \right] \epsilon$$

where ϵ is the distance from the center of gravity. The parameters Ω , g_0 , r_0 and δr are the rotational speed in radians per unit time, the earth's gravitational acceleration, the radius of the earth, and the orbital distance, respectively. For a 90-minute orbit at 350 km,

$$a \approx 4 \times 10^{-6} \epsilon \text{ (L/sec}^2\text{)}.$$

At a distance $\epsilon = 1$ m from the center of gravity, this non-uniformity amounts to about $4 \times 10^{-7} g_0$.

If the vehicle is rotated to maintain a fixed orientation relative to the earth, there is a centrifugal acceleration outwardly directed from the center of gravity of magnitude given by:

$$a = \epsilon \Omega^2$$

For a 90-minute orbit,

$$a \approx 10^{-6} \epsilon (L/\text{sec}^2)$$

The self attraction between two masses can cause an experiment to be subjected to accelerations of a slightly smaller magnitude. The expression is

$$a = \frac{F}{m} = \frac{GM}{r^2} \approx 6.67 \times 10^{-11} \frac{M}{r^2} \text{ (meter/sec}^2\text{)}$$

where M is the disturbing mass in kilograms and r the distance between the bodies in meters. If M is 5000 kg, this effect will be of the same order as the previous two accelerations.

The vehicle will also have an acceleration caused by aerodynamic drag which is a function both of altitude and where in the atmosphere the vehicle is located. At a constant altitude, of say 400 km, the drag on the vehicle will vary with orbital position. Any ellipticity in the orbit will amplify changes in acceleration acting on the experiment.

In essence, what this says is that a "zero" g experiment is next to impossible. Only at $10^{-5} g_0$ or higher are experiments which require precise gravity fields feasible without undue difficulty. Even at $10^{-5} g_0$, care must be taken. The lower the g-level, the greater the possibility of perturbations resulting from the vehicle attitude control system, drag variations, astronaut movement and the performance of other experiments.

For some experiments, a higher g-level may be tolerated in order to mask the non-uniformities in g. Fuel costs and weight penalties may lead the experimentalist to consider rotation to achieve these higher g-levels. If rotation is necessary, two acceleration disturbances are apparent: acceleration gradient and Coriolis acceleration. The acceleration gradient for a rotating vehicle is a/L where a is the rotationally induced acceleration at the experiment and L is the distance from the center of gravity of the vehicle to the center of gravity of the experiment apparatus. For a 1-m experimental tank, a 6-m moment arm is required to make the acceleration change less than

15-20% from the top of the liquid surface to the bottom. For a 15-cm slosh wave, this would result in approximately a 2.5% non-uniformity. The ratio of Coriolis acceleration to linear acceleration is $2 \Omega \times V / a$. For high-amplitude surface disturbances or high-velocity flow, these effects are very important; for a 90-minute orbit, the effects are significant when $g = 10^{-5} g_0$ and $V = 10^{-3}$ m/sec. Low-amplitude, low-speed experiments will be relatively free from such effects providing they are located appropriately far from the center of gravity of the vehicle. For the boiling experiments, the Coriolis acceleration will cause the buoyancy-induced segment of the trajectory of a bubble to deviate from the direction of the gravitational acceleration by as much as 45° when $g = 10^{-6} g_0$ and Ω is appropriate for maintaining earth orientation.

All experiments must be analyzed with the various non-uniformities of the gravity field in mind. In extreme cases, an experiment may be feasible only during an interplanetary flight. Others can simply be conducted at higher g-levels than originally intended. Rotationally generated g-fields have their own problems and may or may not be feasible for some experiments. Tethering of the experiment is a possibility. It has, however, not been explored herein.

G-Jitter

As contrasted to the non-uniformities of the gravity field, some of which must be accepted as part of the natural environment of an orbital vehicle, there are transient or time-varying perturbations to the gravity field at a point. The unsteady perturbations, which have been termed "g-jitter," can arise from two sources: spacecraft maneuvers and mechanical vibrations.

Spacecraft maneuvers can produce g-jitter of varying magnitudes. Attitude control systems, for example, can cause "bumps" of $10^{-4} g_0$ or greater. This problem can, however, be surmounted since, according to current Space Shuttle specifications, a "drift" mode of the vehicle can be maintained for up to 160 hours, during which only atmospheric drag and internal g-disturbances will be present. Experiments can also be planned so that the significant observations are made during shorter drift periods when there are no spacecraft maneuvers.

On the other hand, g-jitter caused by mechanical vibrations can not necessarily be controlled at their sources. Mechanical vibrations that are transmitted to the experiment have the same effect as a time-varying gravity. They can be caused, for example, by astronaut motion, rotating or reciprocating machinery, and extra-vehicular activities. Arm and leg movements by the experimentalist, breathing, "soaring" translations, and console operations such as flipping switches, are all significant in this respect. During the Skylab experiment on crew/vehicle disturbances (Experiment T-013), transient forces of as much as 310 newtons (70 pounds) were measured. Real-time

monitoring of the Skylab rate gyro and attitude data indicated that rotation rates of 0.4 deg/sec resulted from the soaring maneuvers of the astronauts and 0.015 deg/sec during vigorous exercise (ref. 105). Overall, some vibration levels, bumps, and transients have been inferred to be as large as $10^{-3} g_0$ during the Skylab experiments. The frequency spectrum of this random vibration was about one to several thousand hertz.

Transient disturbances at a level of $10^{-3} g_0$ are large enough to make questionable the scientific advantages of conducting controlled experiments in space. Proper attention to isolation of the experiments from vibration can, however, significantly reduce the magnitude of these effects. It is not possible to assess at this time the level of the g-jitter that will be present in the space laboratory; we have based our recommendations on the assumption that careful design of the experiments can make the effects tolerable. Nonetheless, the problems of g-jitter are recognized as being potentially the most difficult obstacle to controlled experimentation in a low-gravity environment. We strongly recommend that further research be conducted for the objectives of defining the g-jitter environment, measuring it, and relating it to the objectives of the proposed experiments.

Cosmic Radiation

All the Space Shuttle orbits are within a natural, magnetically-confined plasma in a hard vacuum. High-energy cosmic particles bombard the Space Shuttle as well. This charged particle stream in space may interfere with charged-droplet and cloud-physics experiments. Abnormal nucleation may be caused by passage of the particles through a gas or liquid during a phase change, especially for those experiments in which a liquid or solid undergoing a phase change is deliberately exposed to vacuum.

Instrumentation

The Committee gave some thought to the kinds of measurements that will have to be made to carry out the experiments and to whether the measurements are influenced by the environment of the space laboratory. No unusual problems were identified, but several kinds of instrumentation must be developed.

A definite need exists for instrumentation that will record the g-jitter level accurately at the location of an experiment.¹ The present method is to back-calculate the g-jitter from recorded rate-gyro and attitude data, but this is of dubious accuracy.

Many of the proposed experiments suggest the use of laser, interferometric holography as an optical measurement technique, but we believe that there is no laser holography apparatus currently available that can withstand the rigors of space flight. Space-flight-rated laser light detection techniques, such as photon-counting, are also needed, as are optical detection and photographic apparatus. Perhaps, there is also a need for temperature-control techniques.

Other, more specialized, apparatus include a wave-probe for measurements of low-gravity wave profiles. With the exception of optical techniques, all wave-probes used in earthbound experiments pierce the free-surface; in space, capillary-induced motion of the liquid could be a problem. Some of the experiments require metering or "weighing" of small liquid masses. Whenever a free-surface is present in low-gravity, the strong capillary forces make metering techniques difficult, and instruments for the precise and accurate direct measurement of mass in the gram or milligram range are not yet available for low-gravity use.

Role of the Principal Investigator

The Committee believes strongly that the Principal Investigator should be actively involved on a real-time basis with the conduct of the experiment in space. In an ideal sense, the Principal Investigator should be the actual experimentalist in space. It is realized, however, that this may not always be feasible for a variety of reasons, such as the time needed for training. In these cases, it would be acceptable for one of his co-workers (such as a graduate student or a member of the research staff) to accompany the experiment and to communicate with the Principal Investigator for making decisions. The Skylab experiments apparently had reasonably good success with this "alter ego" concept (ref. 106). The only alternative to this kind of arrangement is that all data are immediately transmitted to the Principal Investigator while the experiment is in progress so that he can give directions to a technician on board.

CONCLUDING REMARKS AND RECOMMENDATIONS

Without attempting to compile an exhaustive list, the Committee has identified a large number of meritorious experiments in fluid physics, thermodynamics, and heat transfer that would benefit from being conducted in space. The experiments fall into five major groups, as shown by the summary presented in Table 1. This table also shows the interrelationships among the experiments and the need for preliminary studies. Each of the recommended experiments is scientifically meritorious. While a "ranking" has not been assigned to the experiments, the discussion of them in the text has indicated that some of the experiments should be conducted before others. In some cases, the later experiments build upon the knowledge gained in the earlier ones.

Ideally, the Principal Investigator should be the actual in-space experimentalist, but failing this, real-time feedback and control by the Principal Investigator from the ground is a necessity.

Ground-Based Studies

Many of the experiments require ground-based studies to define more precisely the phenomena to be observed and to choose a procedure that will illustrate these phenomena. Here, we are not implying studies to select parameter ranges or hardware design; this is obviously a requirement, but it is properly a part of the design of an experiment after it has already been defined. The recommended ground-based studies, as summarized in Table 1, are of the type that will determine whether an experiment is feasible, and if so, how to maximize the desired effect.

The most important of these ground-based studies include

- . feasibility of preparing a homogeneous sample near the critical mixing point in low-gravity
- . determination of liquids and container materials (or coatings) that minimize hysteresis in the contact angle, for the standing wave experiments, and that have a ninety degree contact angle, for the maximum-amplitude wave experiments, and theoretical studies to define and interpret the experiments
- . studies to define and interpret experiments on liquid- and gas-jet instabilities

- . studies to define experiments on the role of the free-surface and surface tension in convection, and the development of a theory to interpret results on thermoacoustic convection and convection resulting from vibrations
- . estimates of the magnitude of electric fields required to initiate electroconvection effects, and an assessment of the effect of Joulean heating on the process
- . acquisition of understanding needed to establish candidate fluid systems for convection driven by chemical-potential gradients
- . studies to define experiments on bubble coalescence and bubble interaction with a free surface
- . studies to establish the governing dimensionless parameters for thermal stratification in a heated, closed tank of liquid and vapor
- . theoretical and experimental studies to define the experiments on the effect of external fields on boiling.

The Committee also believes that certain instrumentation must be developed to ensure the success of the experiments. The most important are:

- . instrumentation to record accurately the g-jitter level at the experiment location
- . space-flight-rated laser, holographic interferometry system
- . space-flight-rated laser light detection and scattering system
- . low-gravity wave probe.

Every experiment has its own instrumentation requirements; the above instrumentation systems are common to entire classes of experiments.

Title of Experiment	Objective	Commonality with Other Experiments	Ground-Based Studies
<u>I. Critical Point Thermophysical Phenomena</u>			
1. Exploratory studies of phase transition	Study types of low-gravity phase transition phenomena for a pure fluid.	Light-scattering apparatus needed for many experiments; temperature-control bath needed for all Group I experiments.	Determine fluid systems that give optimum performance.
2. Specific heat	Determine fundamental data for equation-of-state.	Objective related to I-2, I-3, I-4, and I-5.	Same as I-1
3. Light-scattering and correlation length	Measure correlation lengths, possibly for samples whose correlation length is of the order of the laser beam size.	Light-scattering apparatus similar to I-1 and IV-1, and experimental technique similar to I-4.	Same as I-1
4. Dielectric constant and refractive index	Measure anomalies in these quantities.	Possibly can be combined with I-3	Same as I-1
5. Velocity of sound	Obtain critical point data at wavelengths and frequencies different than for light-scattering; determine equation-of-state data.	Objective related to I-2	Same as I-1
6. Diameter of coexistence curve	Measure anomalous behavior in co-existing densities.	Experimental procedure determined by results of other Group I experiments.	Design experimental technique.
7. Viscosity	Measure weakly anomalous behavior.	--	Same as I-1
8. Thermal conductivity	Accurately measure critical-point conductivity.	Similar to I-3 but for correlation lengths that are not small compared to wavelength of light.	Same as I-1
9. Exploratory studies with a binary liquid	Study low-gravity phase transition phenomena in binary liquid mixtures.	Objective similar to I-1	Determine feasibility of preparing a homogeneous sample near the critical mixing point.
<u>II. Fluid-Surface Dynamics and Capillarity</u>			
1. Static and dynamic contact angle hysteresis	Determine contact angle phenomena in static and dynamic liquid-solid configurations.	Results will augment II-3, II-4, and III-1, III-2.	No critical studies identified.
2. Configuration of contained liquids	Determine equilibrium free-surface shapes for containers of various geometries, and transient configurations when container is subjected to a change in net acceleration.	Similar apparatus and optical instrumentation as II-3 and II-4.	No critical studies identified.

Title of Experiment	Objective	Commonality with Other Experiments	Ground-Based Studies
3. Maximum-amplitude capillary wave	Determine shape of maximum-amplitude standing and traveling capillary wave.	Optical apparatus similar to II-2; objective related to II-4.	Determine liquid and container systems having 90° contact angle and little contact angle hysteresis.
4. Standing waves in a container	Determine zero-gravity "slosh" modes for various tanks.	Optical apparatus similar to II-2; objective related to II-4.	Determine liquid and container systems having little contact angle hysteresis.
5. Interfacial waves for two superposed liquids	Observe forms of instability.	Apparatus and objective related to II-4.	Same as II-3
6. Droplet formation, breakup, and coalescence	Study interaction between droplets in external acoustic, electric, and thermal fields.	Objective related to IV-3; laser holography technique common to many experiments.	Design of space-rated laser interferometric system.
7. Stability of liquid and gas jets	Exploratory studies of instabilities.	Droplet production studies related to II-7; objective related to II-5.	Studies needed to define experimental conditions
8. Formation of thin films	Determine feasibility of producing thin films by bubble casting.	Spreading related to II-9; heating apparatus common to heat transfer experiments.	No critical studies identified.
9. Spreading of thin films	Fundamental study of spreading of liquids on surfaces, at various g-levels.	Capillary phenomena related to II-1.	Studies needed to define experimental conditions
10. Effects of levitation	Study of advantages of levitation for solidification and liquid-liquid or liquid-solid dispersions.	--	No critical studies identified.
<u>III. Convection at Reduced Gravity</u>			
1. Effect of sidewalls on Marangoni flow	Study effects of container geometry, wettability, and thermal conditions on surface-tension driven flows of a liquid with a free surface.	Objective and apparatus related to III-2, III-3, and IV-4.	Theoretical and experimental studies needed to define experimental conditions.
2. Role of a free-surface on heat transfer	Observe flow regimes (cellular, turbulent, etc.) as a function of geometry, materials, and thermal conditions.	Apparatus similar to III-1; objective related to III-1, III-3, and V-4.	Same as III-1
3. Pressure and temperature conditions in a heated, closed tank of liquid and vapor	Observe convection regimes and determine correlation equations in terms of nondimensional parameters.	Apparatus similar to III-1 and III-2.	Same as III-1
Thermoacoustic convection	Exploratory studies of convection under rapid heating.	--	No critical studies identified; theoretical work needed to interpret results.

Title of Experiment	Objective	Commonality with Other Experiments	Ground-Based Studies
5. Convection resulting from mechanical vibrations	Exploratory studies of heat transfer and flow in a filled container for various vibration inputs.	--	Same as III-4.
6. Convection resulting from electric and magnetic fields	Fundamental studies of electroconvection, electro-osmosis, electrophoresis, and magnetically driven flows.	Instrumentation similar to III-4, III-5, and II-7.	Assessment of Joulean heating effects.
7. Solutal convection	Exploratory experiments to define flows driven by concentration gradients.	Objective and apparatus related to III-8.	No critical studies identified.
8. Thermosolutal convection	Exploratory studies to define flows resulting from coupling of thermal and concentration gradients.	Objective and apparatus related to III-7.	No critical studies identified.
9. Convection driven by gradients in chemical potential	Fundamental studies of types of possible motions.	Procedure and apparatus related to III-11.	Acquire fundamental understanding needed to establish candidate fluid systems.
10. Convection driven by combined effects of surface tension and other forces	Exploratory studies to define various flow regimes.	Objective and apparatus related to III-7 and III-8.	Determine fluid systems that give optimum performance.
11. Thermally unstable flows	Measure velocity and temperature fields and transition from cellular flow to turbulence.	Procedure similar to III-9; holographic interferometry common to many experiments.	No critical studies identified.
IV. <u>Non-Heated Multiphase Mixtures</u>			
1. Dynamics of aerosols	Determine long-term size distribution and stability.	Light scattering apparatus similar to I-3.	No critical studies identified.
2. Formation, stability, and behavior of foams	Studies of characteristics of foams and role of surface tension.	Same as IV-1.	No critical studies identified.
3. Mechanics of liquid-liquid dispersions	Measurements of properties and behavior of liquid-liquid dispersion.	Light scattering apparatus similar to I-3; objective related to II-7.	Selection of liquid systems to emphasize desired phenomena.
4. Bubble dynamics	Determine mechanics of coalescence process, types of bubble motion, and interaction with free-surface.	Optical and photographic techniques common to several experiments.	Studies to define experimental conditions.
V. <u>Multiphase Heat Transfer</u>			
1. Effect of gravity on boiling curve	Determine role of gravity in incipient boiling, nucleate boiling, peak flux, transition, and film boiling.	Apparatus and objective related to V-2, V-3, and V-4.	No critical studies identified.
2. Bubble forces in nucleate boiling	Fundamental studies of forces acting on bubbles in nucleate boiling.	Same comments as V-1.	No critical studies identified.

Title of Experiment	Objective	Commonality with Other Experiments	Ground-Based Studies
3. Mechanics of bubble microlayer	Exploratory studies of role of microlayer in boiling heat transfer	Laser interferometric system similar to III-11.	No critical studies identified.
4. Marangoni effect of bubbles	Determine role of surface-tension driven flow in vicinity of bubbles in heated liquids.	Objective related to III-1 and III-2.	Selection of liquid-vapor systems to emphasize desired phenomena.
5. Effect of external fields on boiling	Exploratory studies of effects of acoustic, electric, and magnetic fields on boiling heat transfer.	Objective related to III-3, III-6, V-1, and V-II.	Ground-based studies needed to define experiments.
6. Forced convection boiling	Exploratory studies to determine transients and instabilities.	Equipment common with V-7.	Same comments as V-5.
7. Forced-flow condensation in tubes	Exploratory studies of instabilities and limitations of method.	Equipment common with V-6.	Same comments as V-5.
8. Evaporation and condensation from augmented surfaces	Fundamental studies of mechanisms and flow regimes of evaporation and condensation at a meniscus.	Objective related to III-2 and V-7. Holographic interferometric system common to many experiments.	No critical studies identified.
9. Solidification and cooling by liquid impingement	Exploratory measurements of obtainable cooling rates when a liquid impinges on a solid surface.	Apparatus related to II-6 and other heat transfer experiments.	Selection of fluid systems and design for maximum cooling rate.

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